GLUING TOGETHER CONSTITUENT QUARKS

Craig D. Roberts

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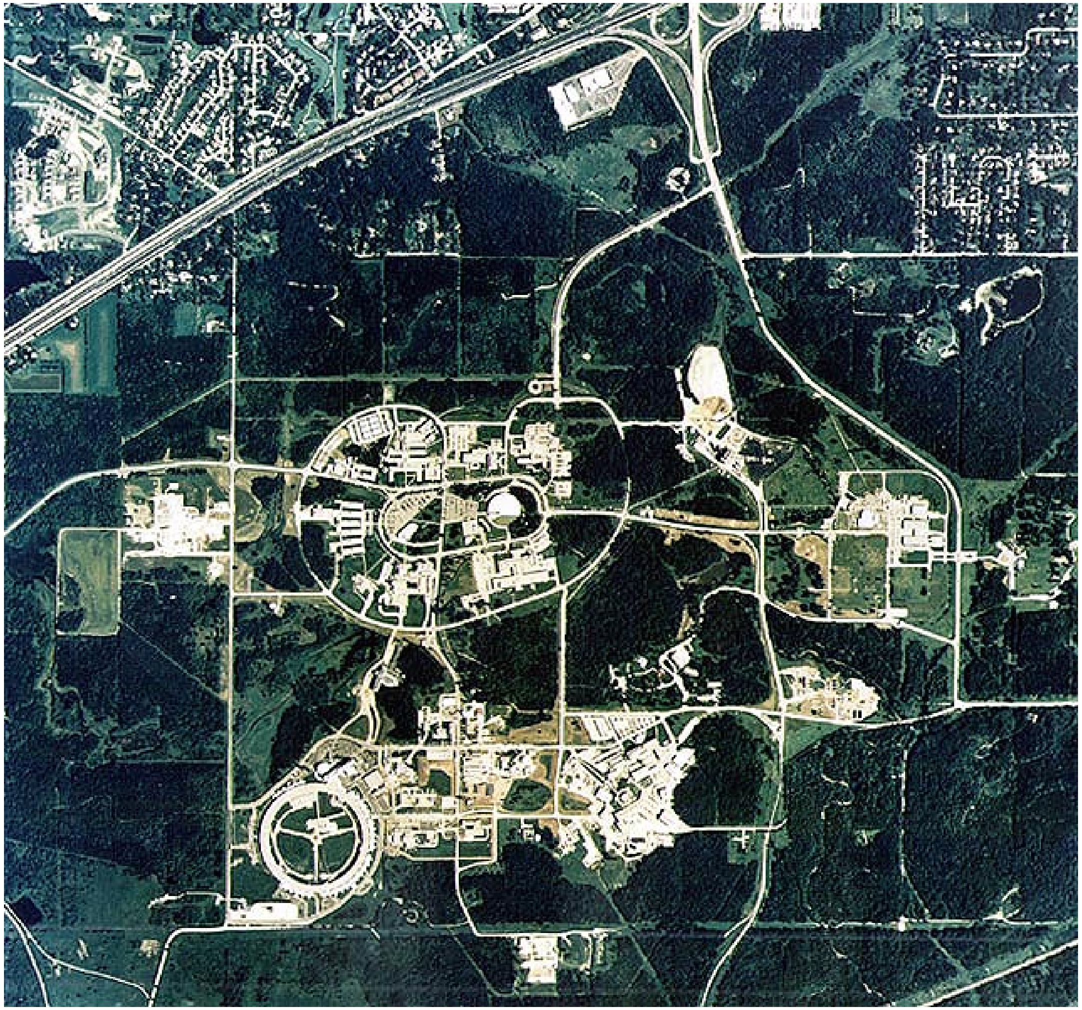
Physics Division

Argonne National Laboratory

http://www.phy.anl.gov/theory/staff/cdr.html

Argonne National Laboratory



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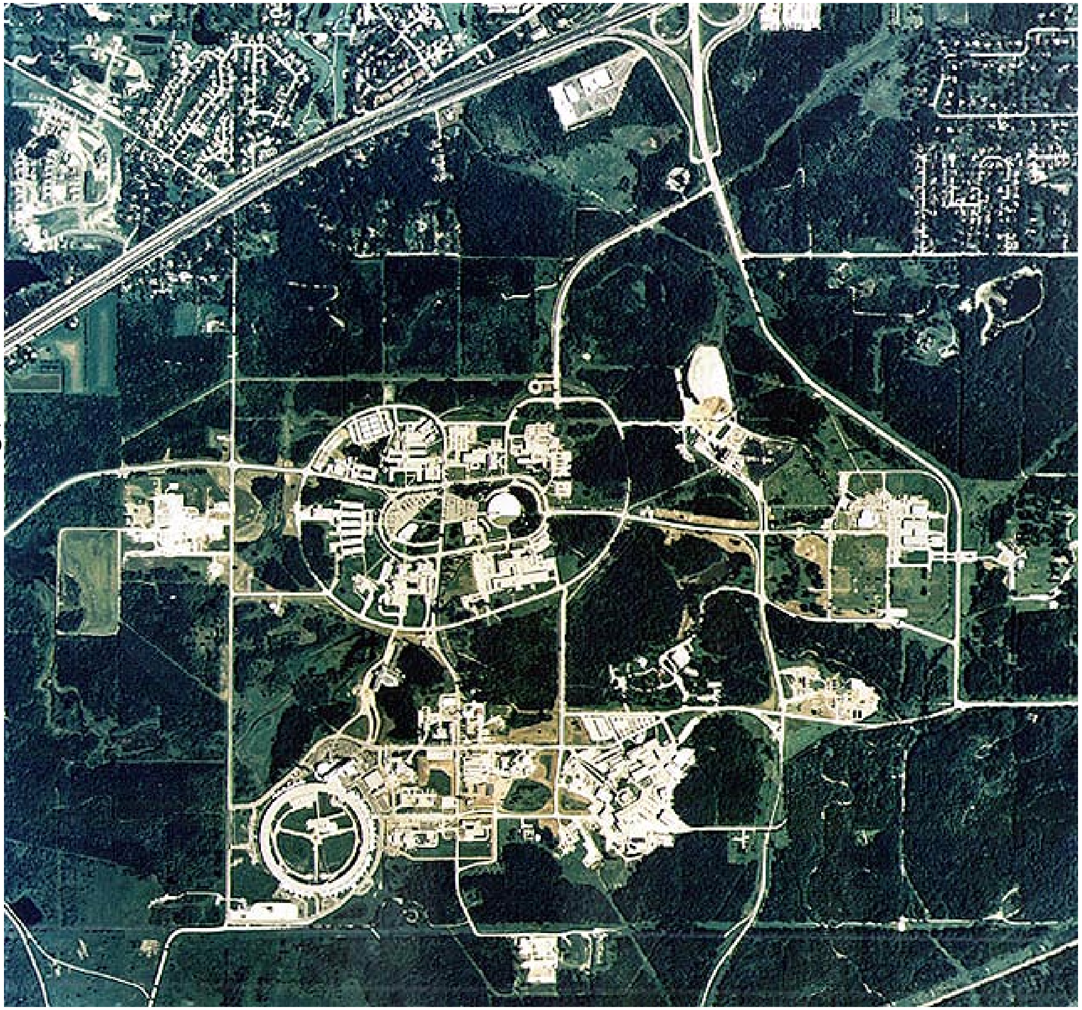
Argonne National Laboratory

Physics Division

- ATLAS Tandem Linac Low Energy Nuclear Physics
- 35 PhD Scientific Staff
- Annual Budget: $22 million



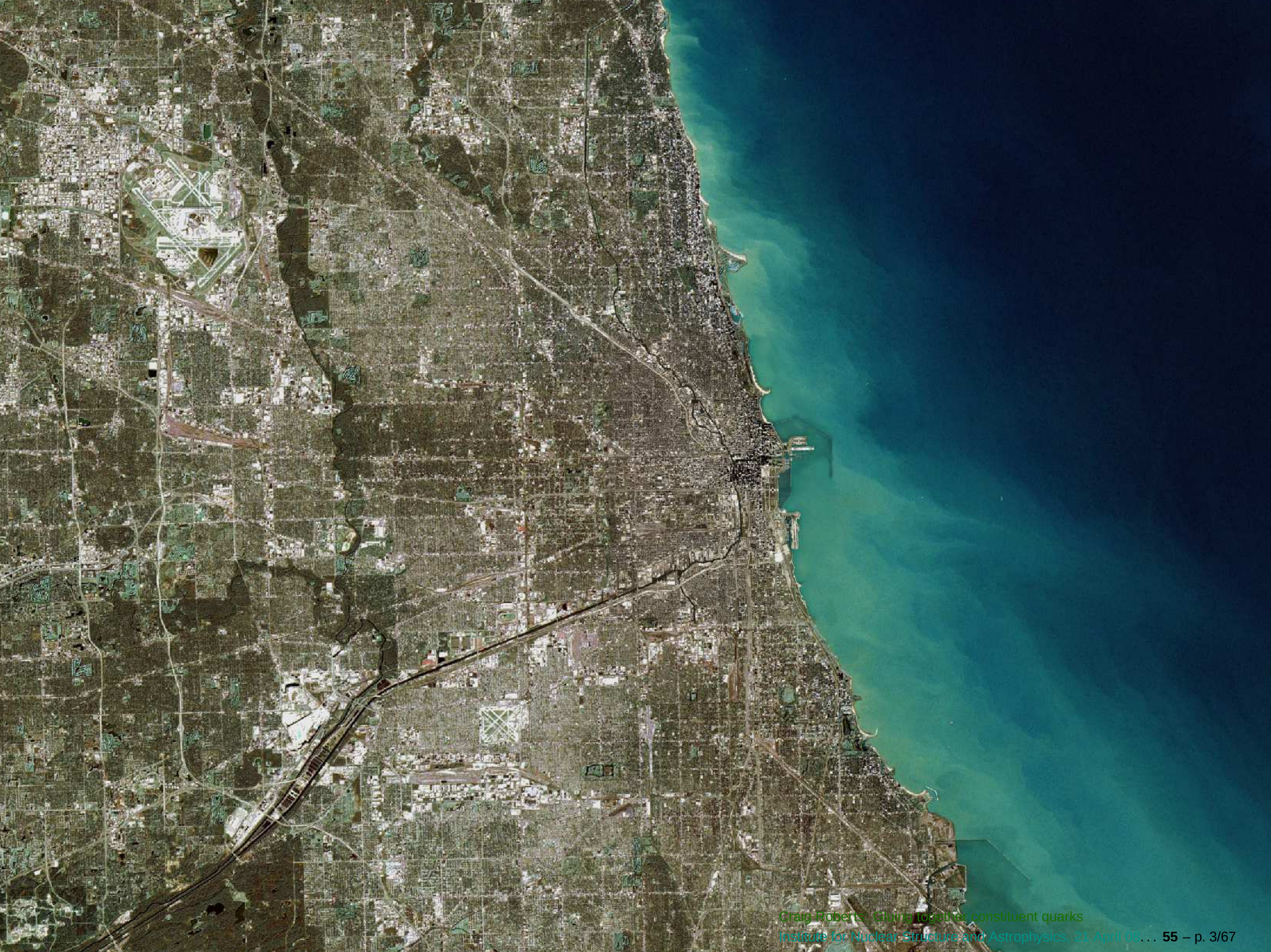
Argonne National Laboratory

Theory Group

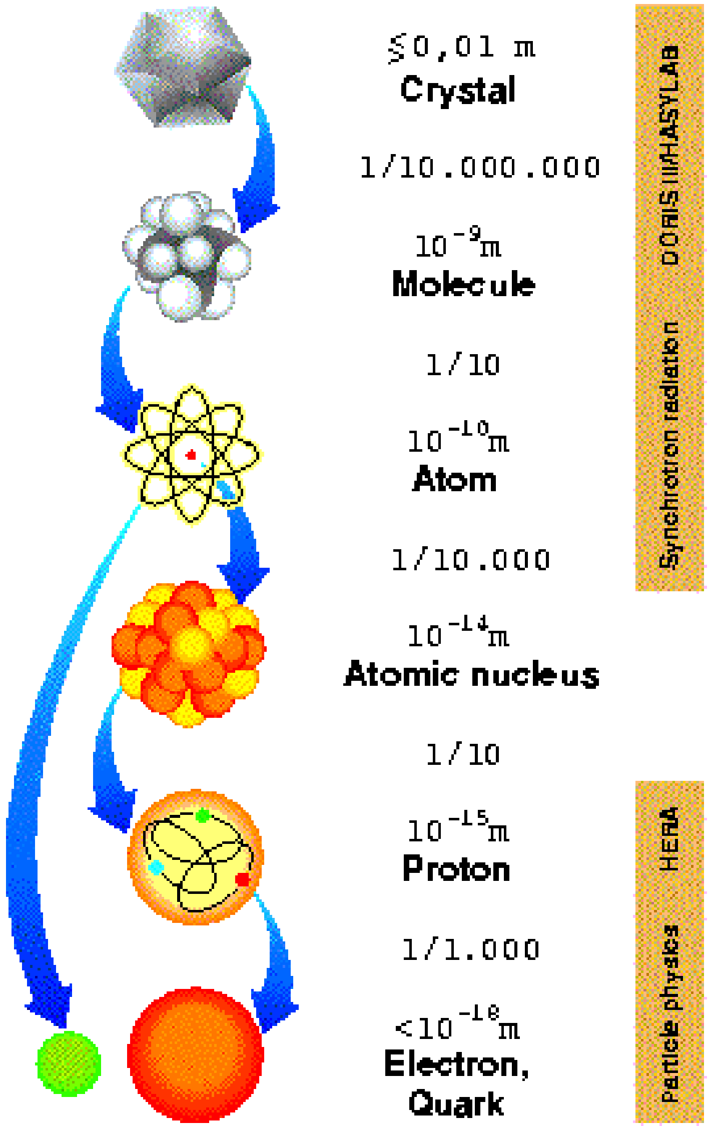
- 7 Staff
- 5 Postdocs
- 7 Special Term Appointees

Our research addresses the five key questions that comprise the USA's nuclear physics agenda. We place heavy emphasis on the prediction of phenomena accessible at Argonne's ATLAS facility, at JLab, and at other laboratories around the world; and on anticipating and planning for FRIB.

Our research explores problems in: theoretical and computational nuclear astrophysics; quantum chromodynamics and hadron physics; light-hadron reaction theory; ab-initio many-body calculations based on realistic two- and three-nucleon potentials; and coupled-channels calculations of heavy-ion reactions. Our programs provide much of the scientific basis for the drive to physics with rare isotopes. Additional research in the Group focuses on: atomic and neutron physics; fundamental quantum mechanics; quantum computing; and tests of fundamental symmetries and theories unifying all the forces of nature, and the search for a spatial or temporal variation in Nature's basic parameters. The pioneering development and use of massively parallel numerical simulations using hardware at Argonne and elsewhere is a major component of the Group's research.



Hadron Physics



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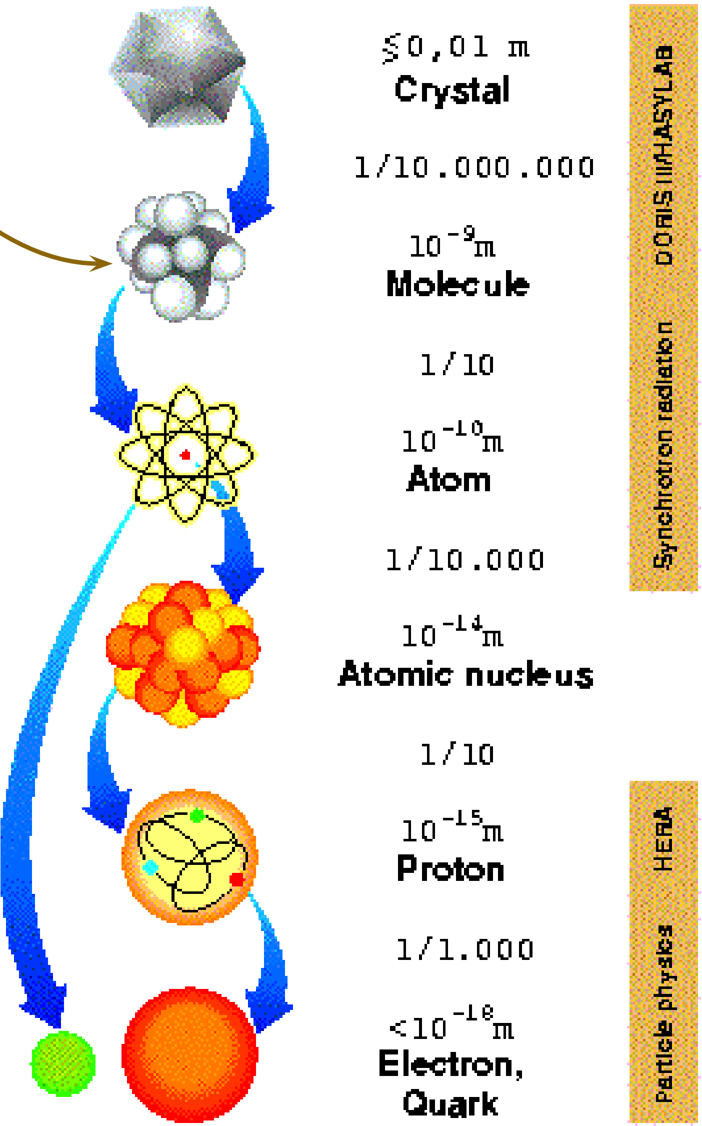
Hadron Physics

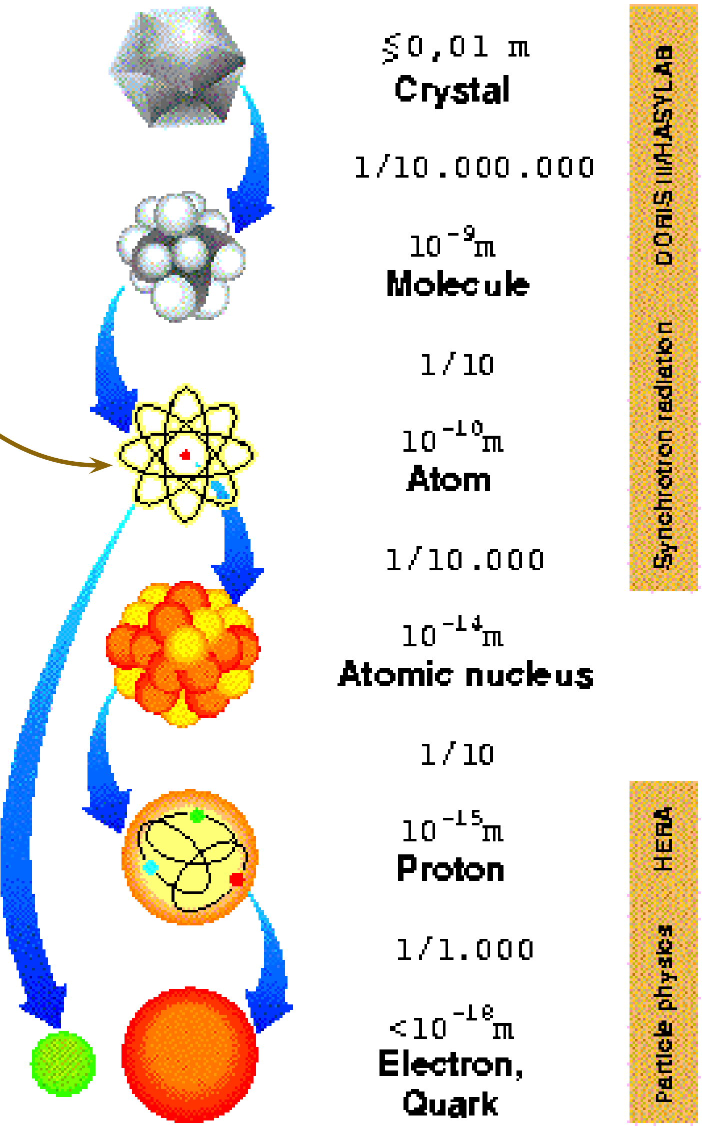
Molecular Physics
Scale = nm



Hadron Physics

Atomic Physics

Scale = Å



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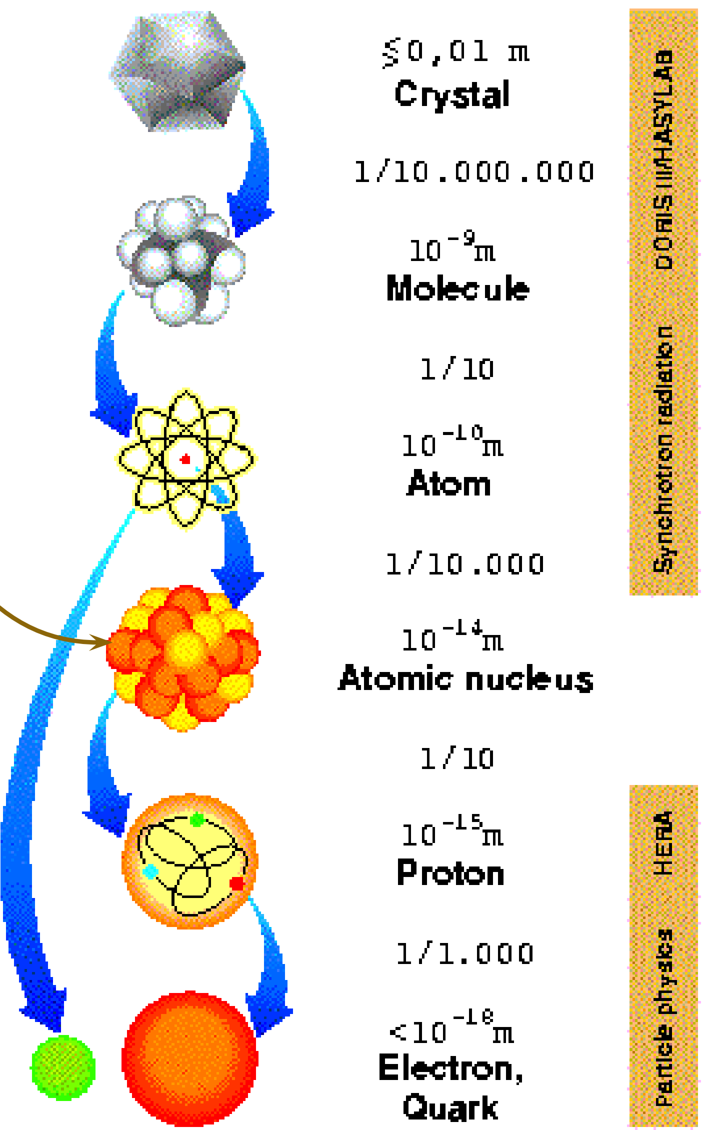
Hadron Physics

Nuclear Physics
Scale = 10 fm



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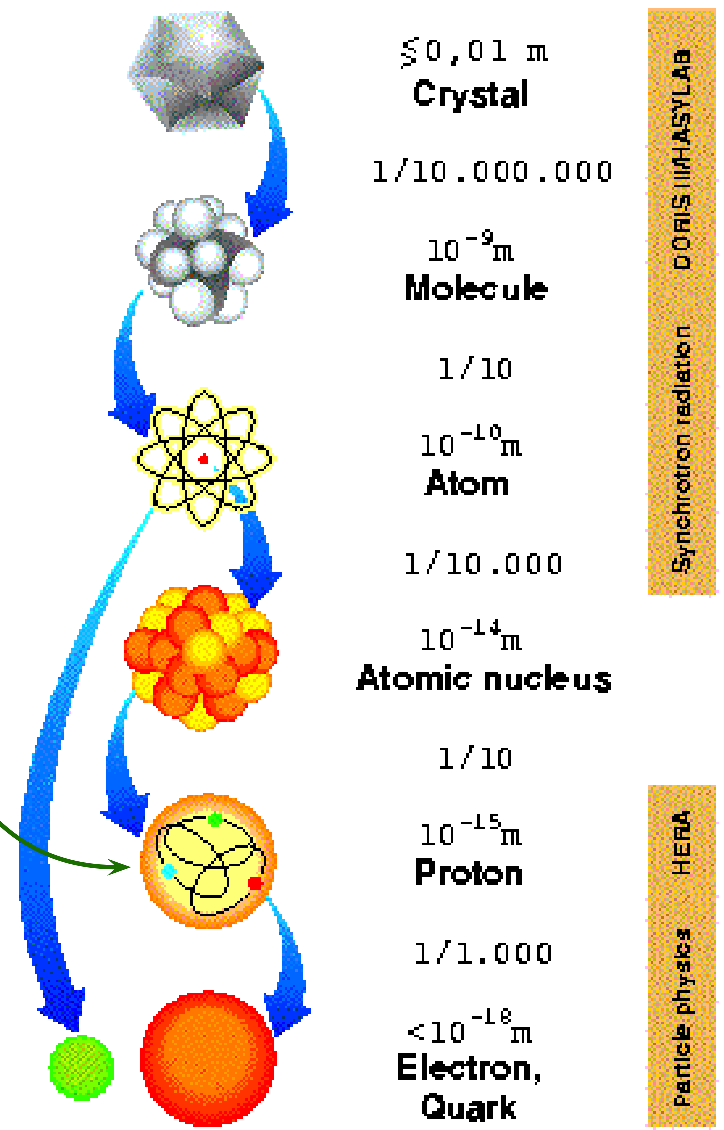
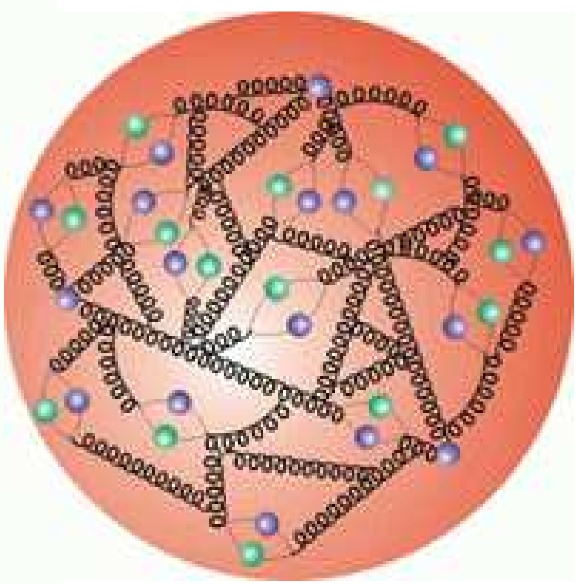
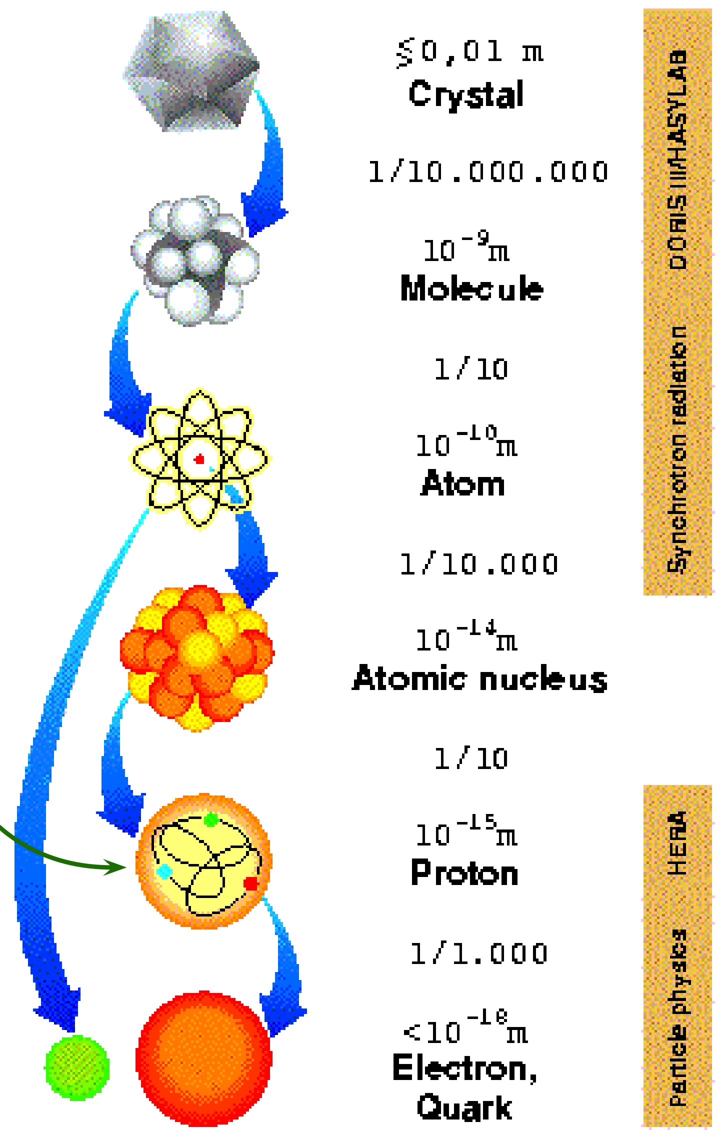
Hadron Physics
Scale = 1 fm

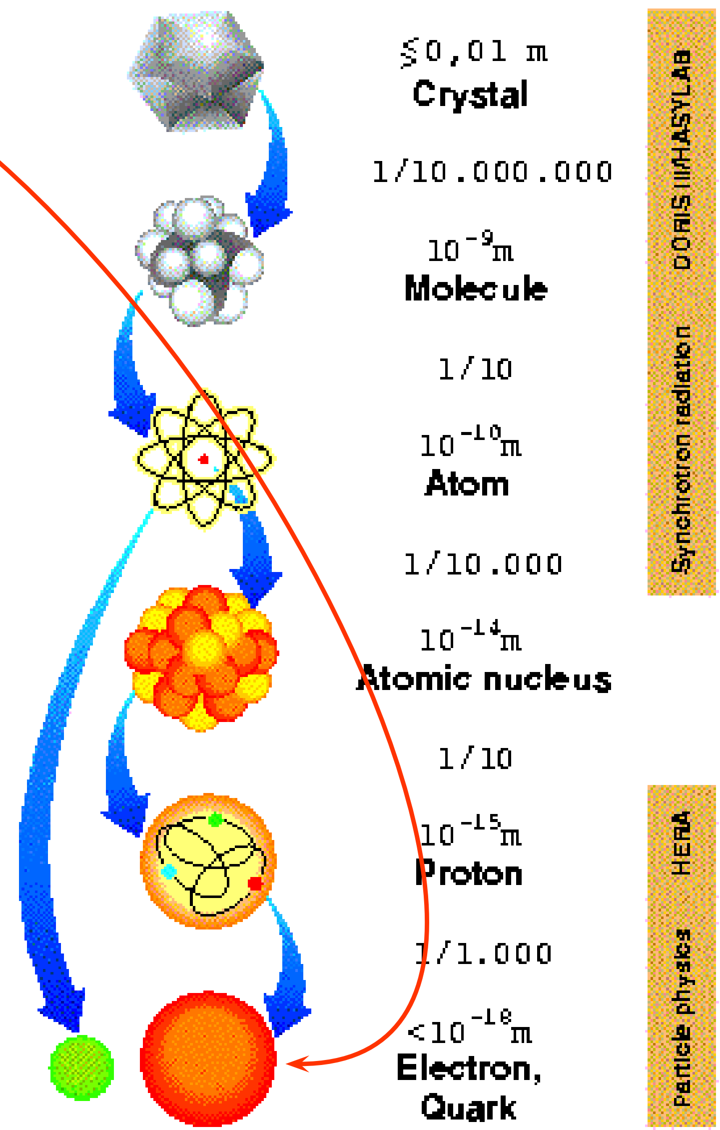


Hadron Physics
Scale = 1 fm





Meta-Physics
Scale = Limited only
by Theorists
Imagination



Nucleon . . . 2 Key Hadrons
= Proton and Neutron

Nucleon . . . 2 Key Hadrons $=$ Proton and Neutron

- Fermions – two static properties:
  proton electric charge $= +1$; and magnetic moment, μ_p

Office of Science
U.S. DEPARTMENT OF ENERGY
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars
Argonne NATIONAL LABORATORY

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Nucleon . . . 2 Key Hadrons
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- Fermions – two static properties:
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- Stern (1933) – $\mu_p = (1 + 1.79)\dfrac{e\hbar}{2M}$
  - Big Hint that Proton is not a point particle
  - Proton has constituents
  - These are Quarks and Gluons
    Quark discovery via $e^- p$-scattering at SLAC in 1968
    – the elementary quanta of Quantum Chromo-dynamics

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What is QCD?

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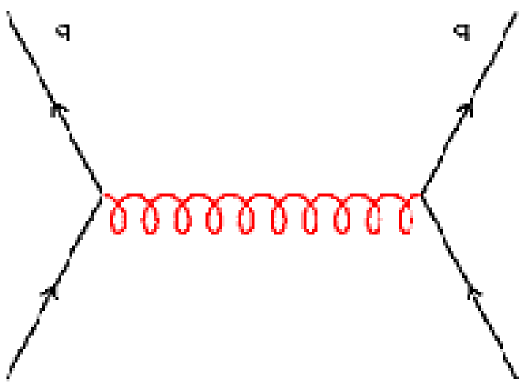
What is QCD?

- Gauge Theory:

  Interactions Mediated by massless vector bosons

Feynman Diagram of Quark–Quark Scattering



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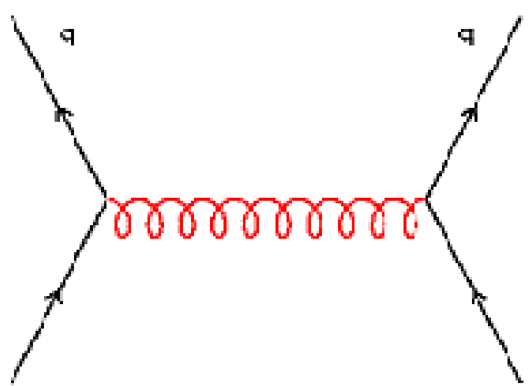

- Similar interaction in QED

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What is QCD?

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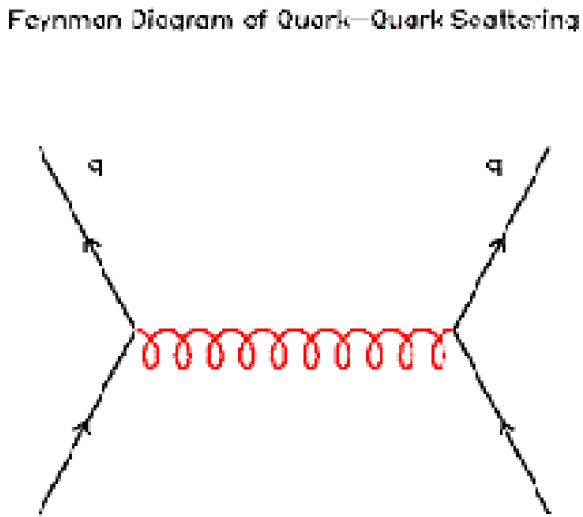

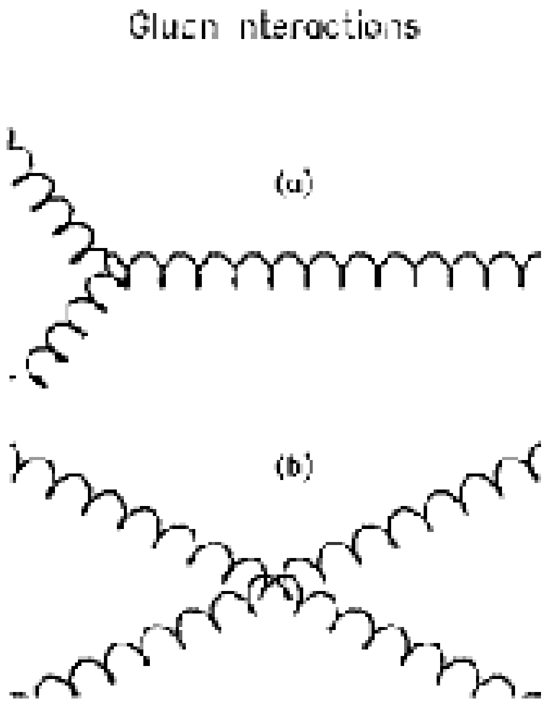

- Similar interaction in QED

- Special Feature of QCD – gluon self-interactions

  Completely Change the Character of the Theory

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QED cf. QCD

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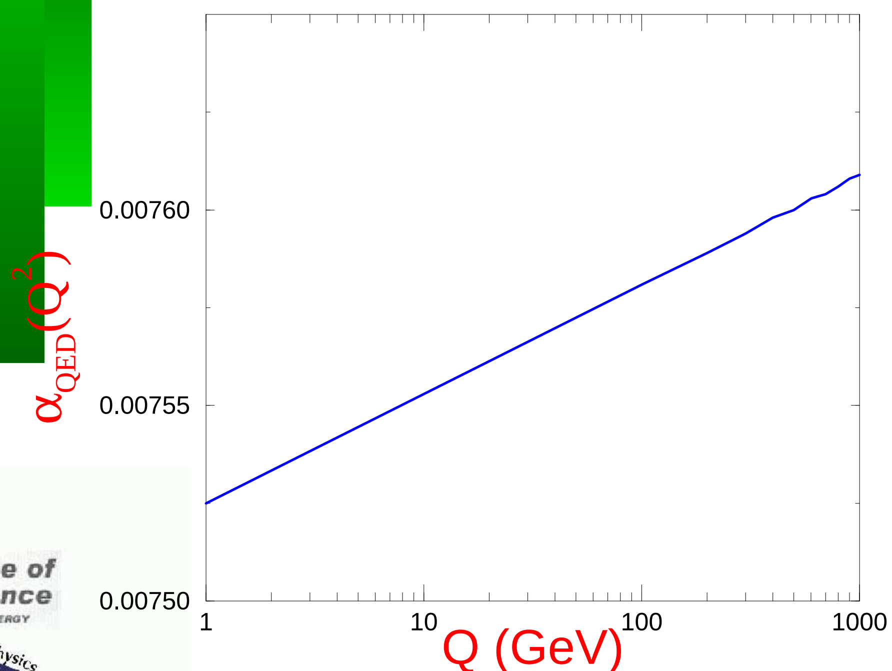
QED cf. QCD



$$\alpha_{\mathrm{QED}} = \frac{\alpha}{1 - \alpha/3\pi \ln\left(Q^2/m_e^2\right)}$$

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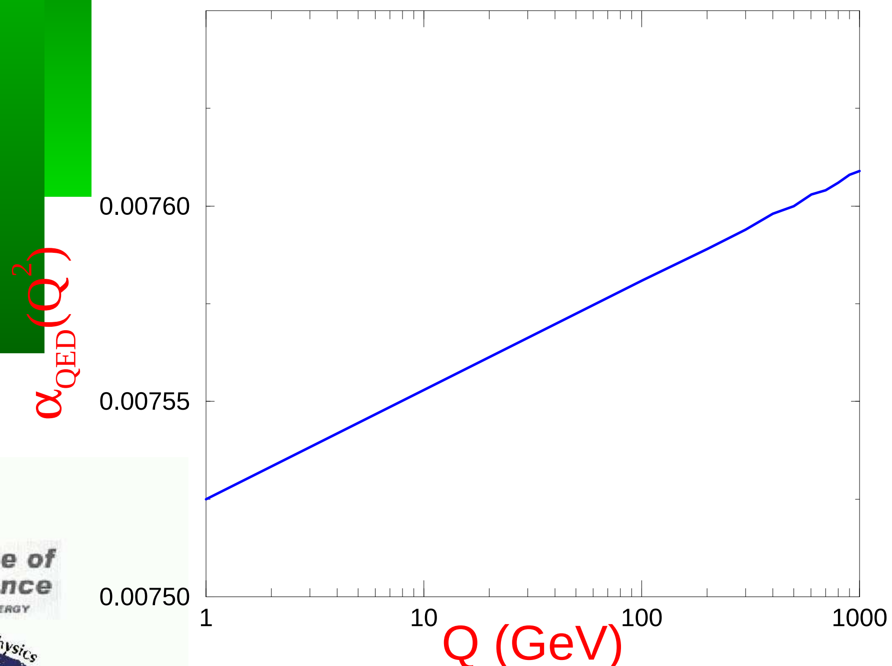
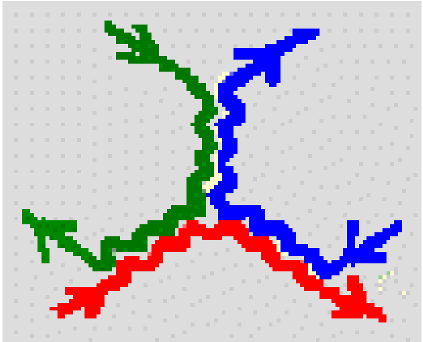
QED cf. QCD

Add three-gluon interaction





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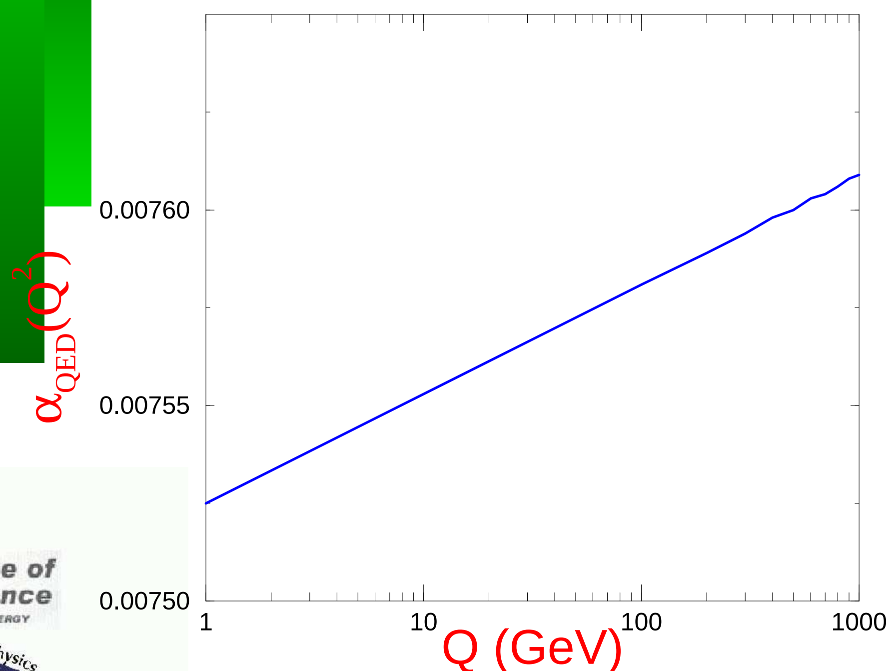


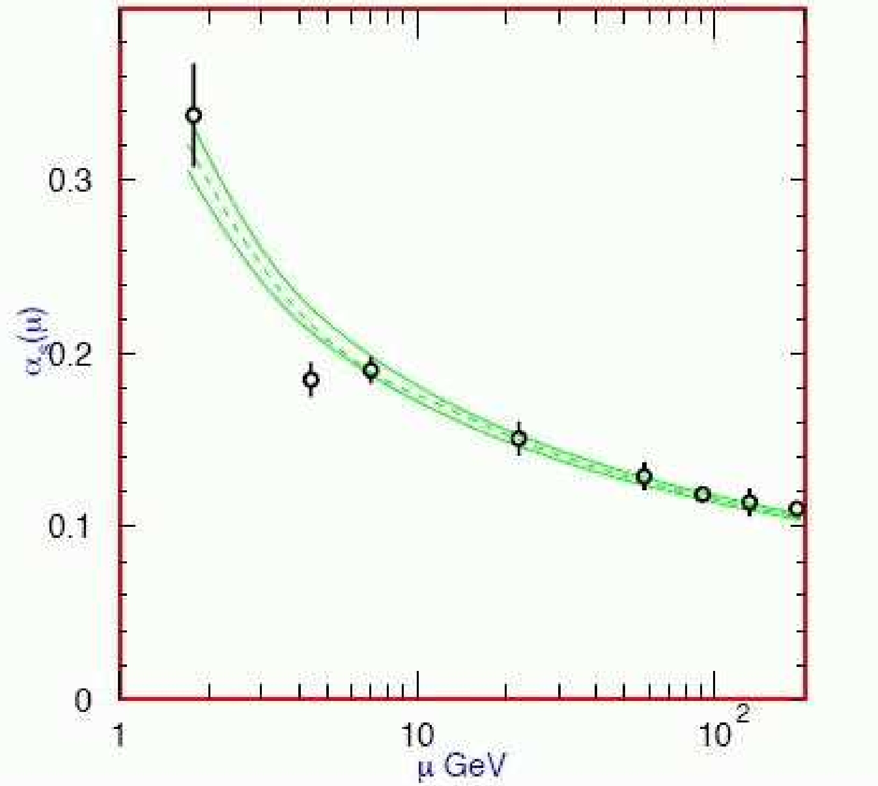
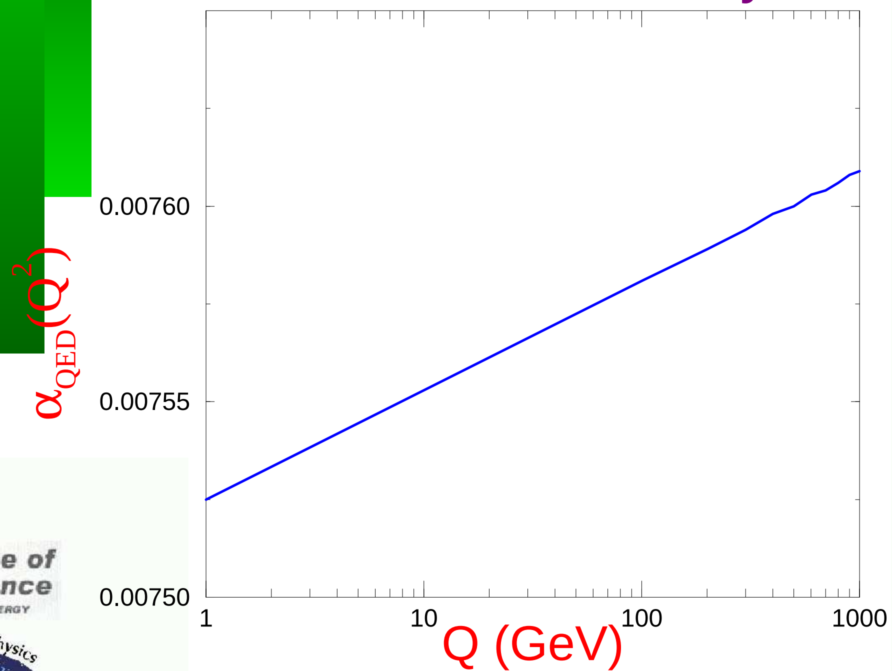


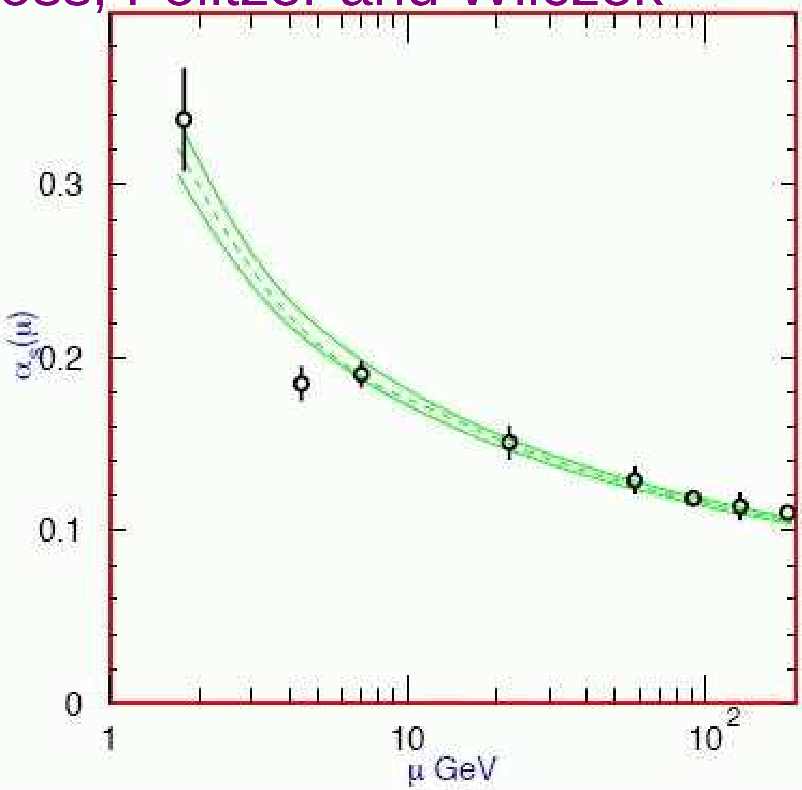
Figure 9.2: Summary of the values of $\alpha_s(\mu)$ at the values of μ where they are measured. The lines show the central values and the $\pm 1\sigma$ limits of our average. The figure clearly shows the decrease in $\alpha_s(\mu)$ with increasing μ. The data are, in increasing order of μ, τ width, Υ decays, deep inelastic scattering, e^+e^- event shapes at 22 GeV from the JADE data, shapes at TRISTAN at 58 GeV, Z width, and e^+e^- event shapes at 135 and 189 GeV.

$$\alpha_{\rm QED} = \frac{\alpha}{1 - \alpha/3\pi \ln\left(Q^2/m_e^2\right)}$$

$$\alpha_{\rm QCD} = \frac{12\pi}{(33 - 2N_f)\ln\left(Q^2/\Lambda^2\right)}$$

2004 Nobel Prize in Physics: Gross, Politzer and Wilczek





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$$\alpha_{\mathrm{QED}} = \frac{\alpha}{1 - \alpha/3\pi \ln\left(Q^2/m_e^2\right)}$$

$$\alpha_{\mathrm{QCD}} = \frac{12\pi}{(33 - 2N_f)\ln\left(Q^2/\Lambda^2\right)}$$

Quarks and Nuclear Physics

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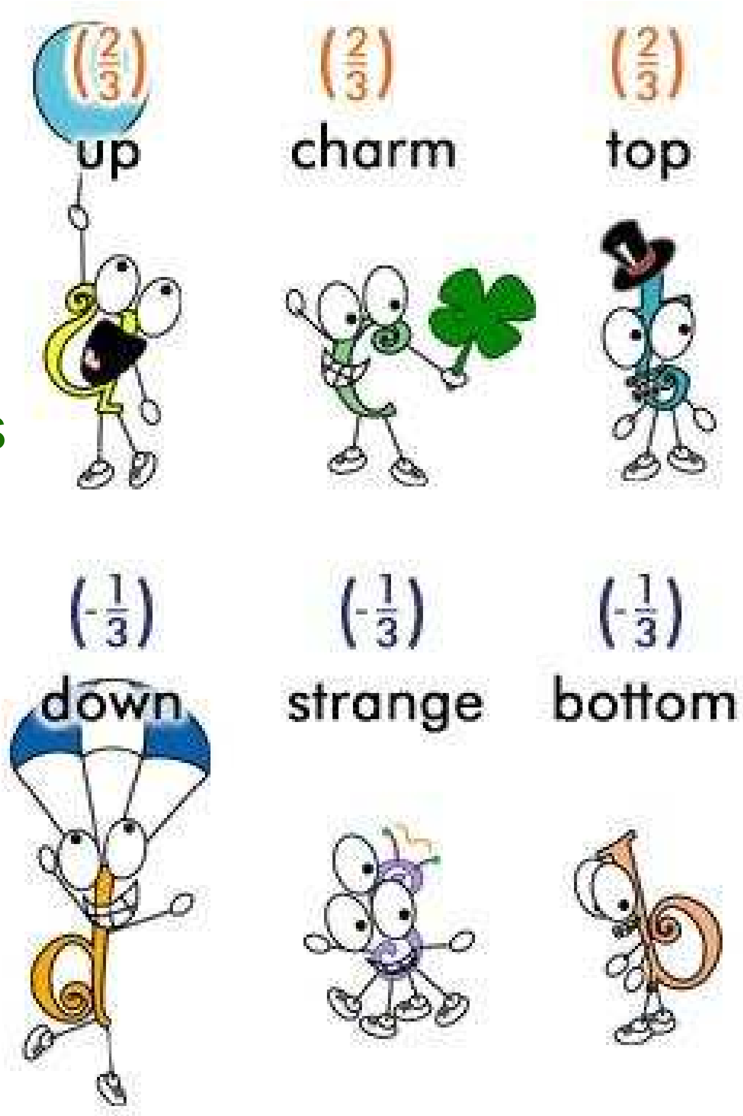
Standard Model

of Particle Physics

Six Flavours



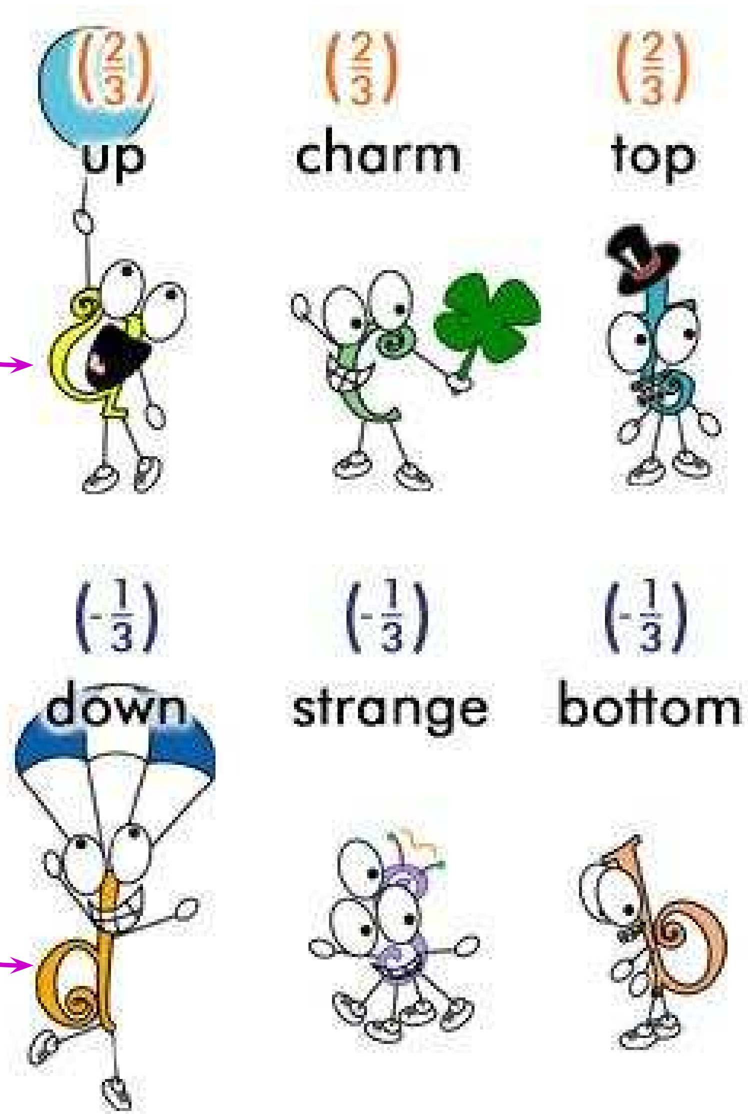
Quarks and Nuclear Physics

Real World

Normal Matter . . .

Only Two Light

Flavours Active



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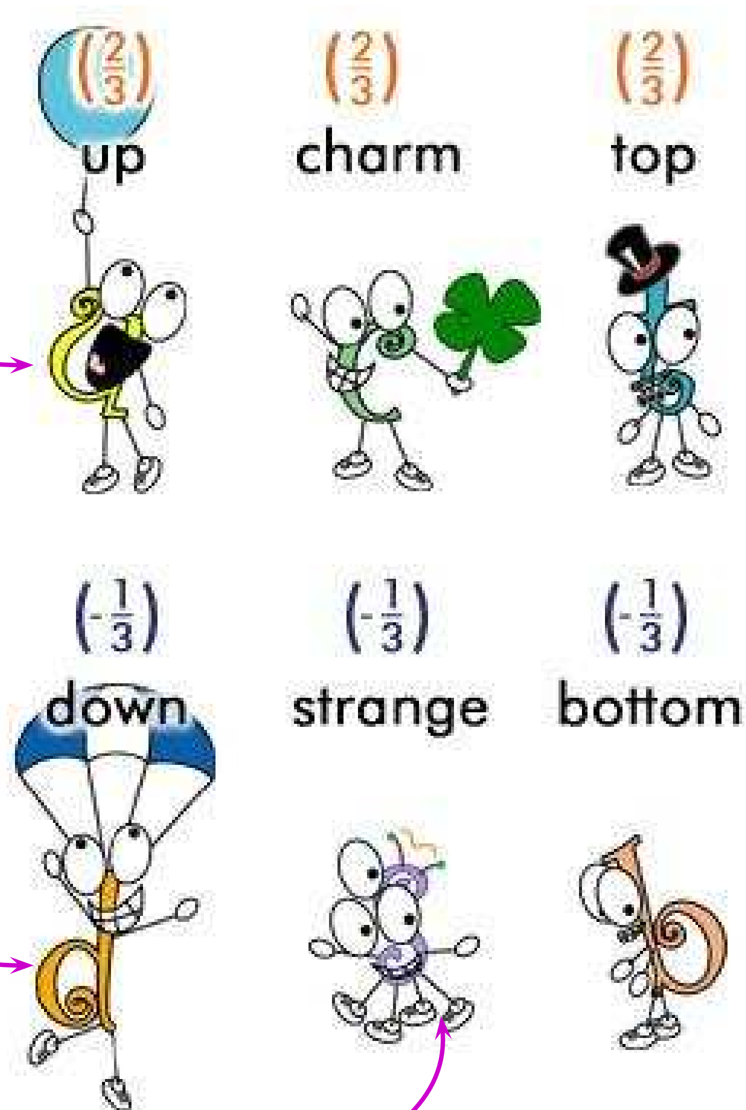
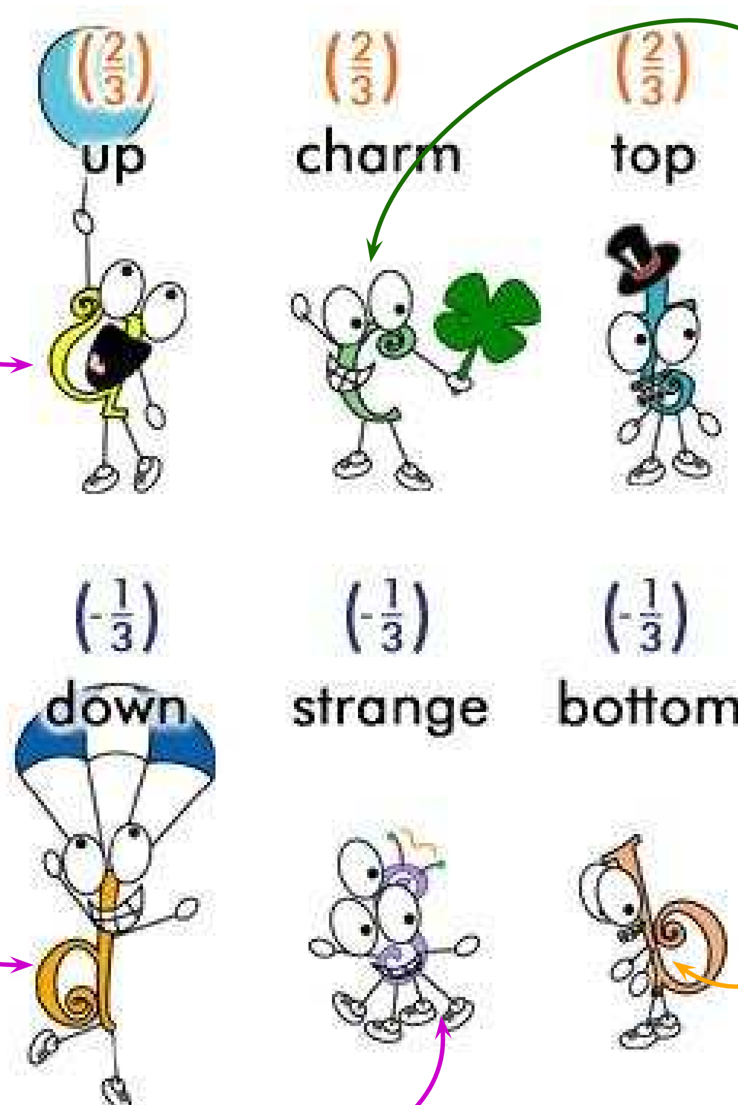


or, perhaps, three

Quarks and Nuclear Physics



Real World

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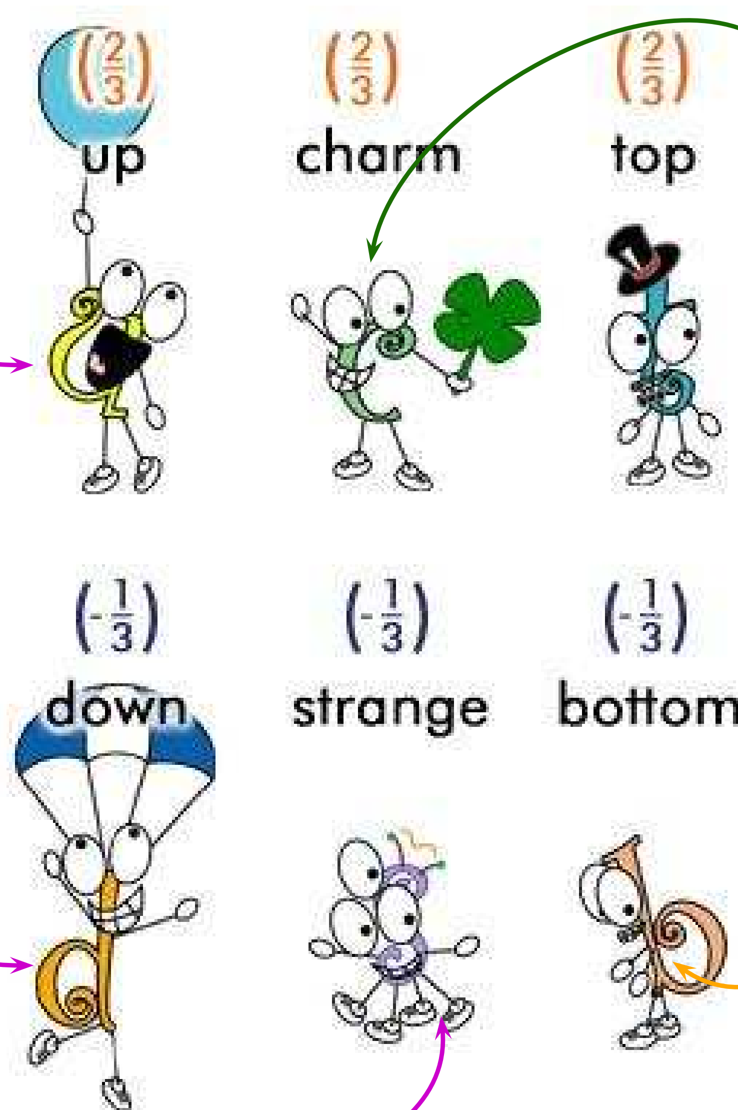
For numerous good reasons, much research also focuses on accessible heavy-quarks

Quarks and Nuclear Physics

Nevertheless, I will focus primarily on the light-quarks.



For numerous good reasons, much research also focuses on accessible heavy-quarks

Real World
Normal Matter . . .
Only Two Light Flavours Active

or, perhaps, three

Simple Picture

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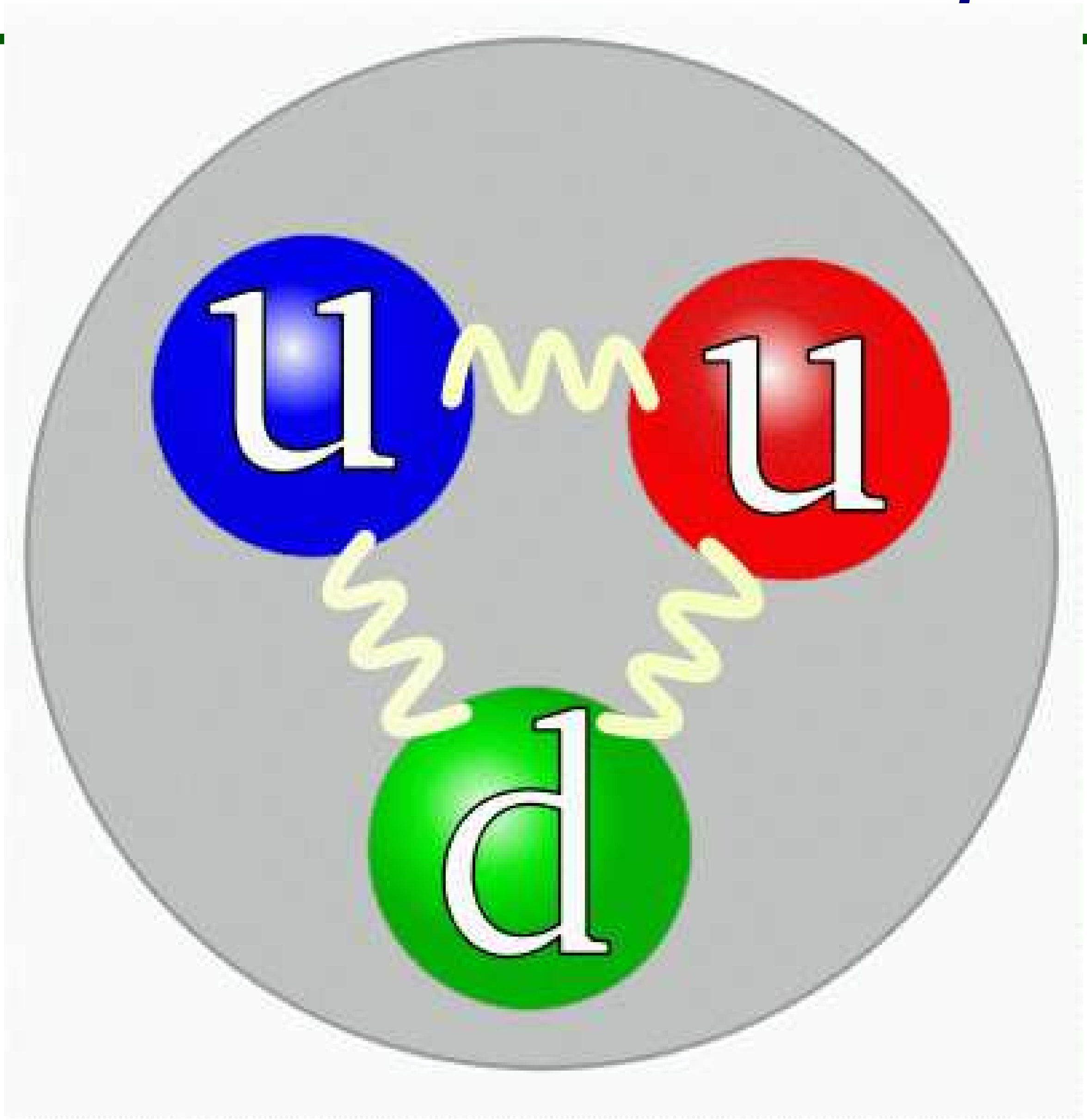
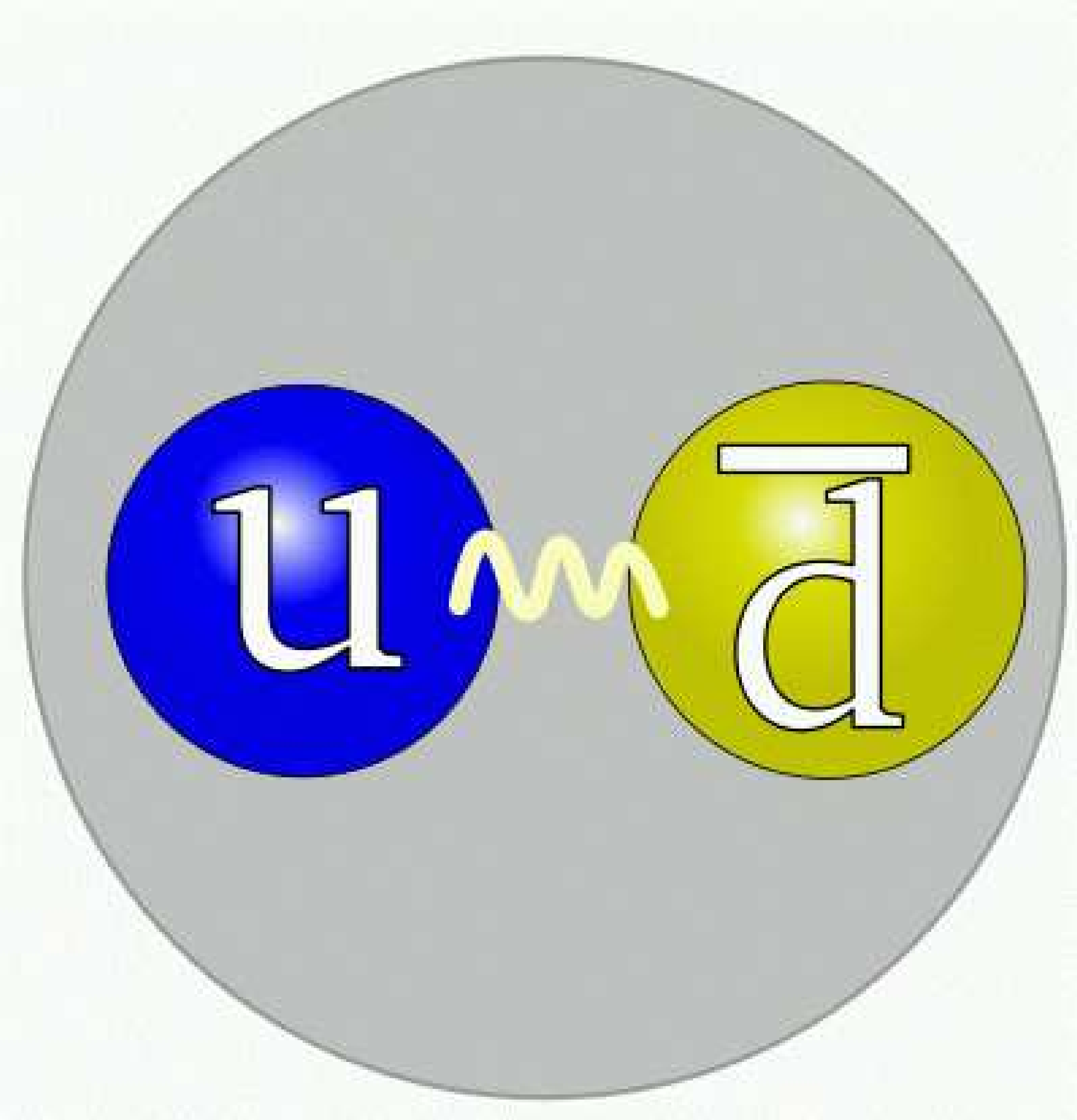
Simple Picture



PROTON

Simple Picture



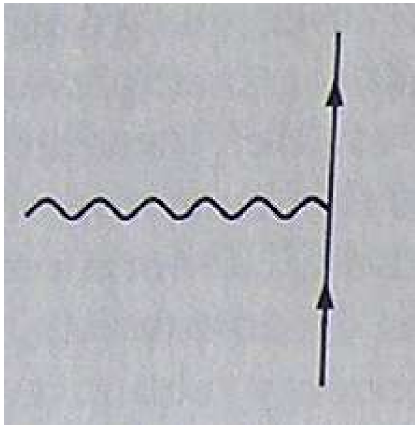
PION

Study Structure via Nucleon Form Factors

Study Structure via Nucleon Form Factors

- Electron's relativistic electromagnetic current:

$$\begin{aligned} j_\mu(P',P) &= ie\,\bar{u}_e(P')\,\Lambda_\mu(Q,P)\,u_e(P)\,,\; Q = P' - P \\ &= ie\,\bar{u}_e(P')\,\gamma_\mu(-1)\,u_e(P) \end{aligned}$$



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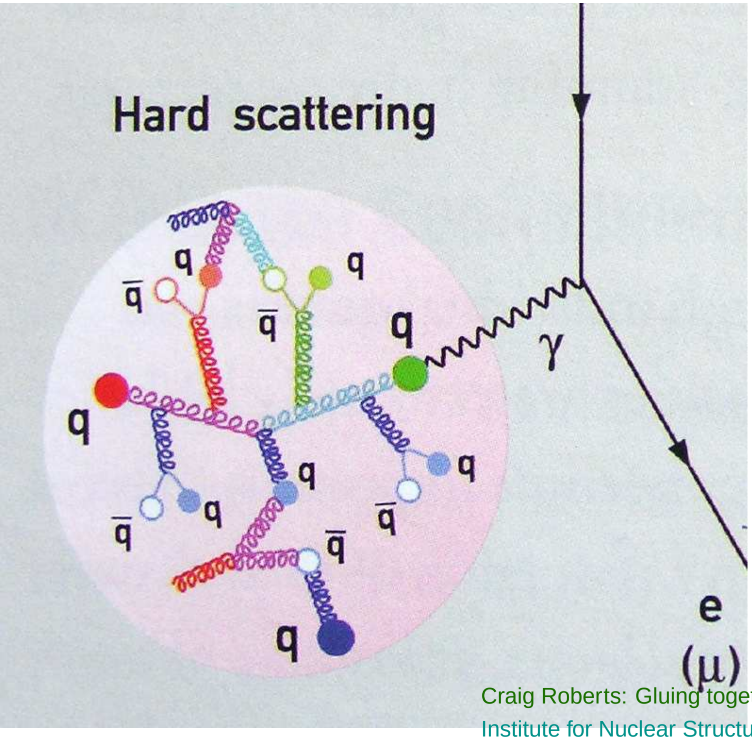

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$$= \;\; ie\,\bar{u}_p(P')\,\left(\gamma_\mu F_1(Q^2) + \frac{1}{2M}\,\sigma_{\mu\nu}\,Q_\nu\,F_2(Q^2)\right)u_p(P)$$

$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M^2}F_2(Q^2)\,,\;G_M(Q^2) = F_1(Q^2)+F_2(Q^2)\,.$$

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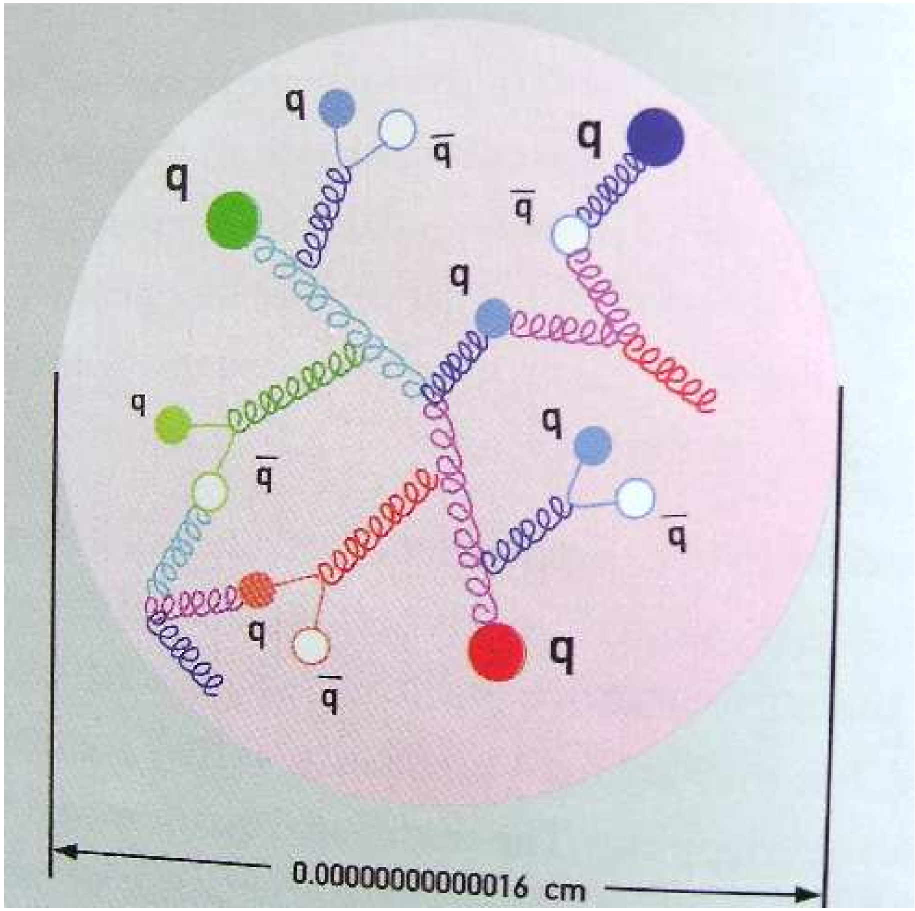
Point-particle: $\boldsymbol{F_2 \equiv 0} \Rightarrow \boldsymbol{G_E \equiv G_M}$

NSAC Long Range Plan

A central goal of nuclear physics is to understand the structure and properties of protons and neutrons, and ultimately atomic nuclei, in terms of the quarks and gluons of QCD



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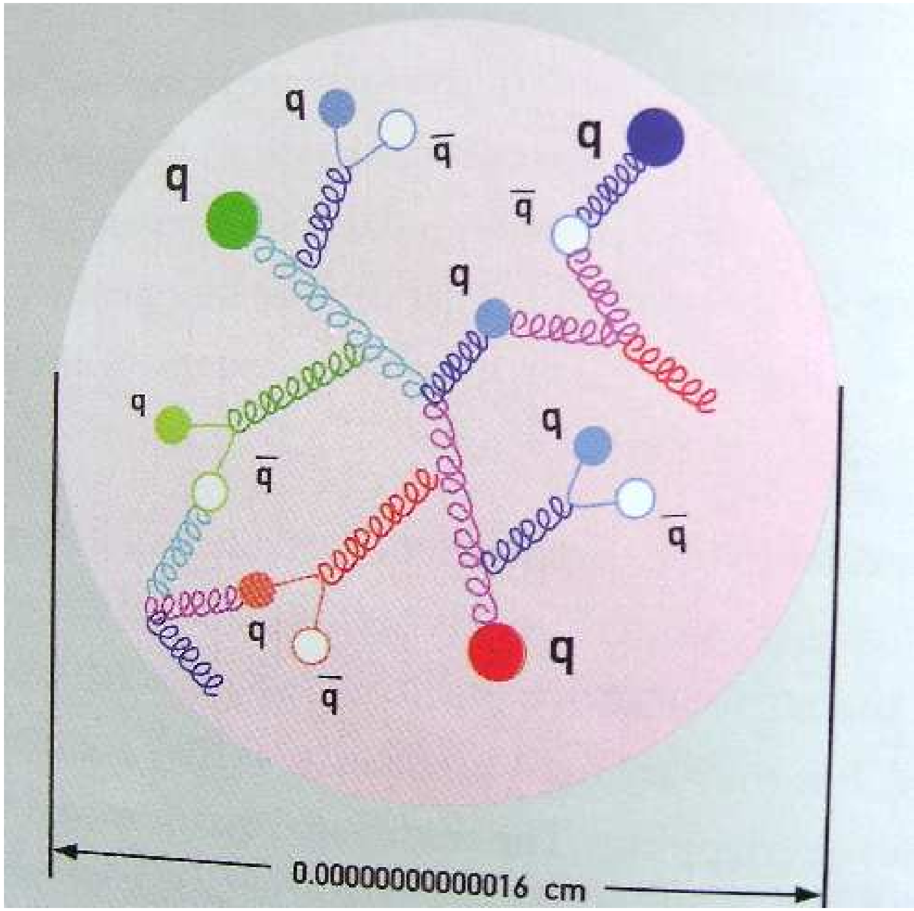

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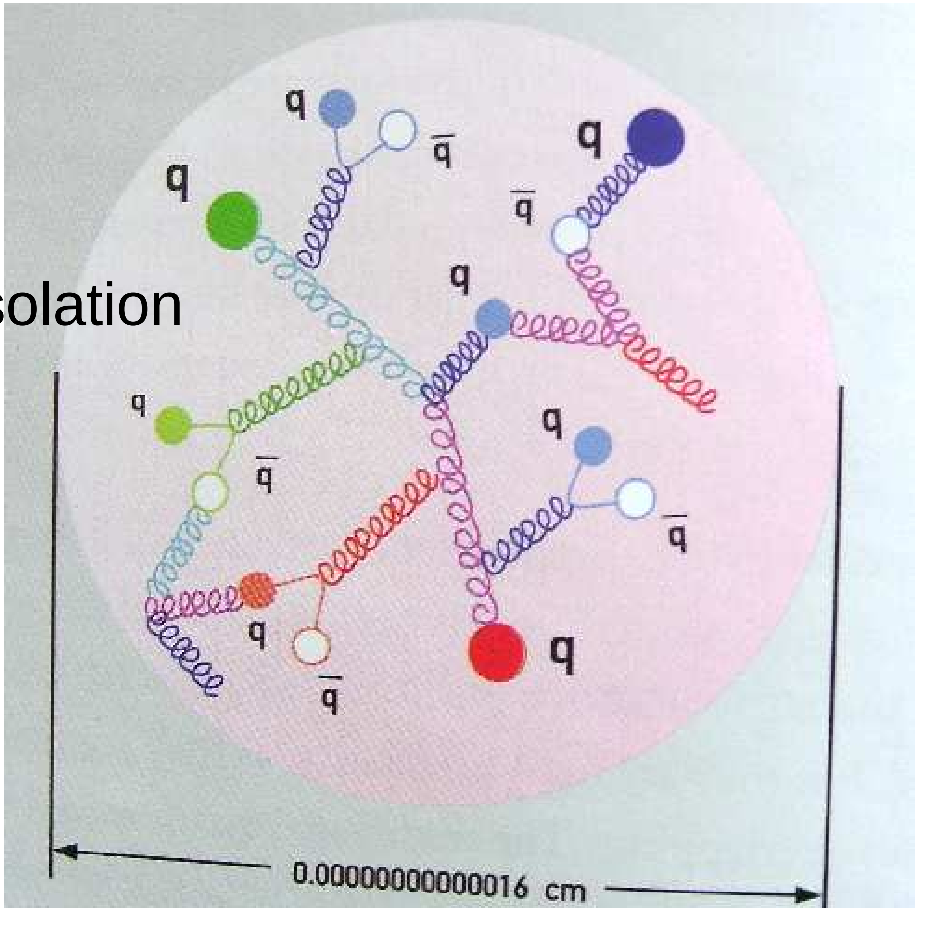
  – No quark ever seen in isolation



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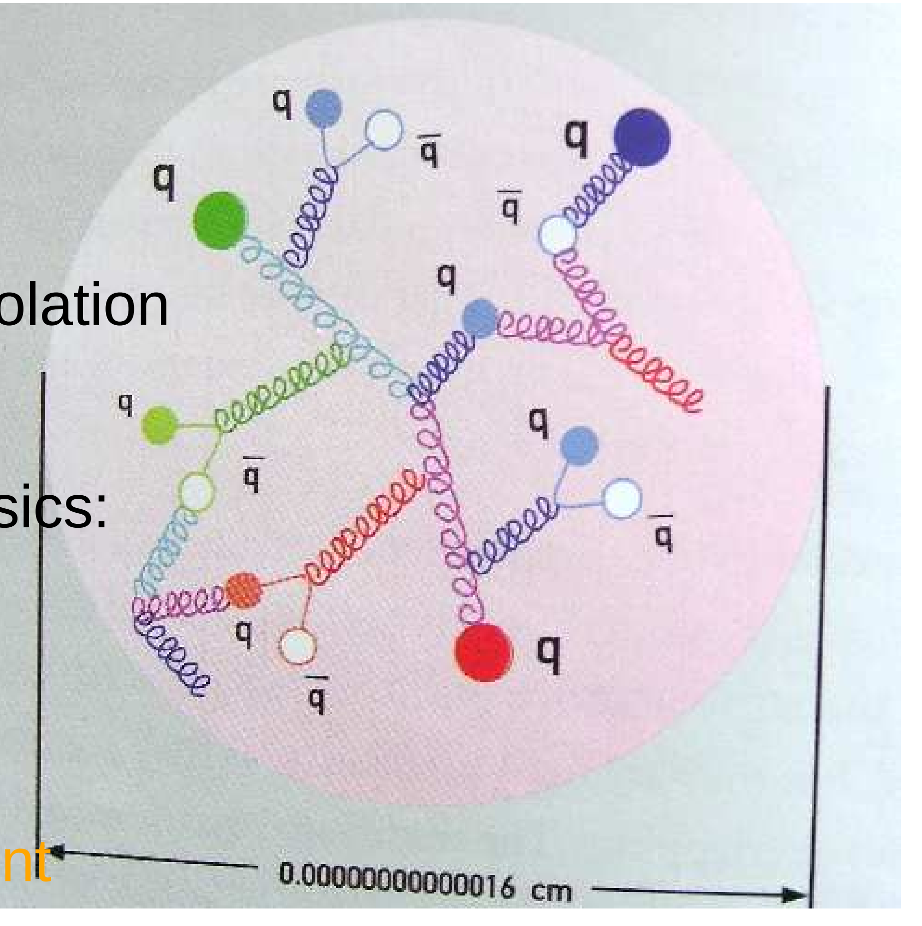
A central goal of nuclear physics is to understand the structure and properties of protons and neutrons, and ultimately atomic nuclei, in terms of the quarks and gluons of QCD

So, what's the problem?

- Confinement
  – No quark ever seen in isolation
- Weightlessness
  – 2004 Nobel Prize in Physics:
  Mass of $u-$ & $d-$quarks,
  each just 5 MeV;
  Proton Mass is 940 MeV
  $\Rightarrow$ No Explanation Apparent
  for 98.4 % of Mass

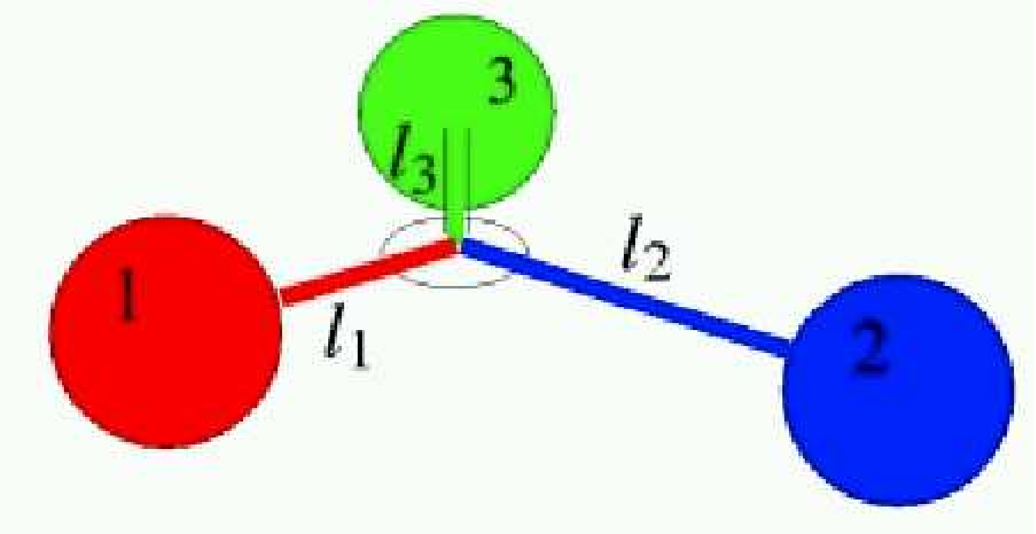


Meson Spectrum

LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$	STRANGE ($S = \pm 1$, $C = B = 0$)	$I(J^P)$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$	• $K^\pm$	$1/2(0^-)$
• π^0 140 MeV	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$	• K^0	$1/2(0^-)$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$	• K^0_S	$1/2(0^-)$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$	• K^0_L	$1/2(0^-)$
• $\rho(770)$ 770	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$	$K^*_0(800)$	$1/2(0^+)$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$	• $K^*(892)$	$1/2(1^-)$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$	• $K_1(1270)$	$1/2(1^+)$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$	• $K_1(1400)$	$1/2(1^+)$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$	• $K^*(1410)$	$1/2(1^-)$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$	• $K^*_0(1430)$	$1/2(0^+)$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$	• $K^*_2(1430)$	$1/2(2^+)$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$	$K(1460)$	$1/2(0^-)$
• $a_1(1260)$	$1^-(1^{++})$	$\rho(1900)$	$1^+(1^{--})$	$K_2(1580)$	$1/2(2^-)$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1910)$	$0^+(2^{++})$	$K(1630)$	$1/2(?^?)$
• $f_1(1285)$	$0^+(1^{++})$	• $f_2(1950)$	$0^+(2^{++})$	$K_1(1650)$	$1/2(1^+)$
• $\eta(1295)$	$0^+(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$	• $K^*(1680)$	$1/2(1^-)$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$	• $K_2(1770)$	$1/2(2^-)$

Modern Miracles in Hadron Physics

- proton $=$ three constituent quarks



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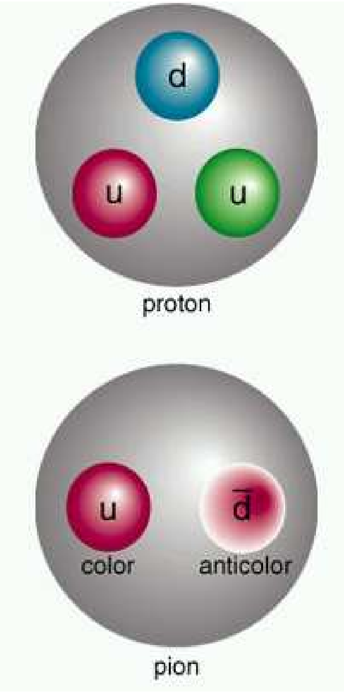
- guess $M_{\mathbf{constituent-quark}} \approx \dfrac{\mathbf{1\,GeV}}{\mathbf{3}} \approx \mathbf{350\,MeV}$
- pion =
  constituent quark + constituent antiquark



- proton $=$ three constituent quarks
- $M_{\rm proton} \approx 1\,{\rm GeV}$
- guess $M_{\rm constituent-quark} \approx \dfrac{1\,{\rm GeV}}{3} \approx 350\,{\rm MeV}$
- pion $=$
  constituent quark $+$ constituent antiquark
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- Another meson:
  . . . . $M_\rho = 770\,\text{MeV}$ . . . . No Surprises Here

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- What is "wrong" with the pion?

Dichotomy of Pion

– Goldstone Mode and *Bound state*

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Highly Nontrivial

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  - Interaction between quarks – the Interquark “Potential” – unknown throughout $>$ 98% of a hadron's volume

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Intranucleon Interaction

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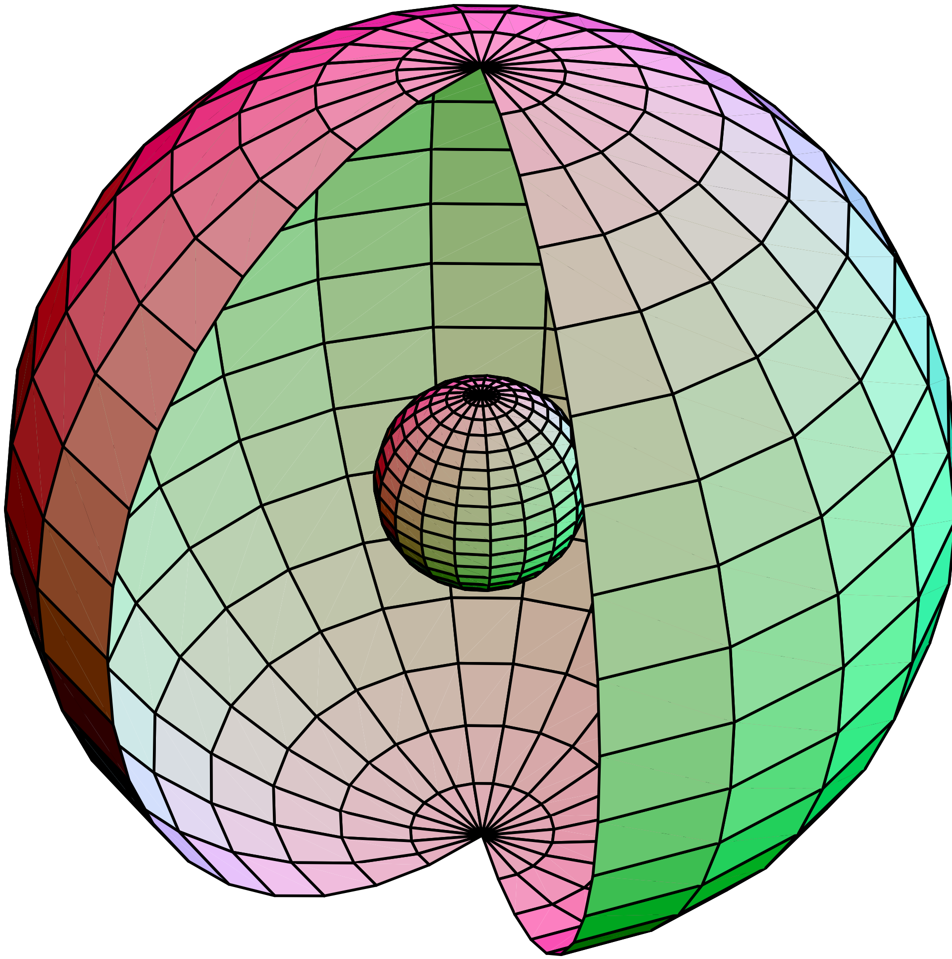
Intranucleon Interaction



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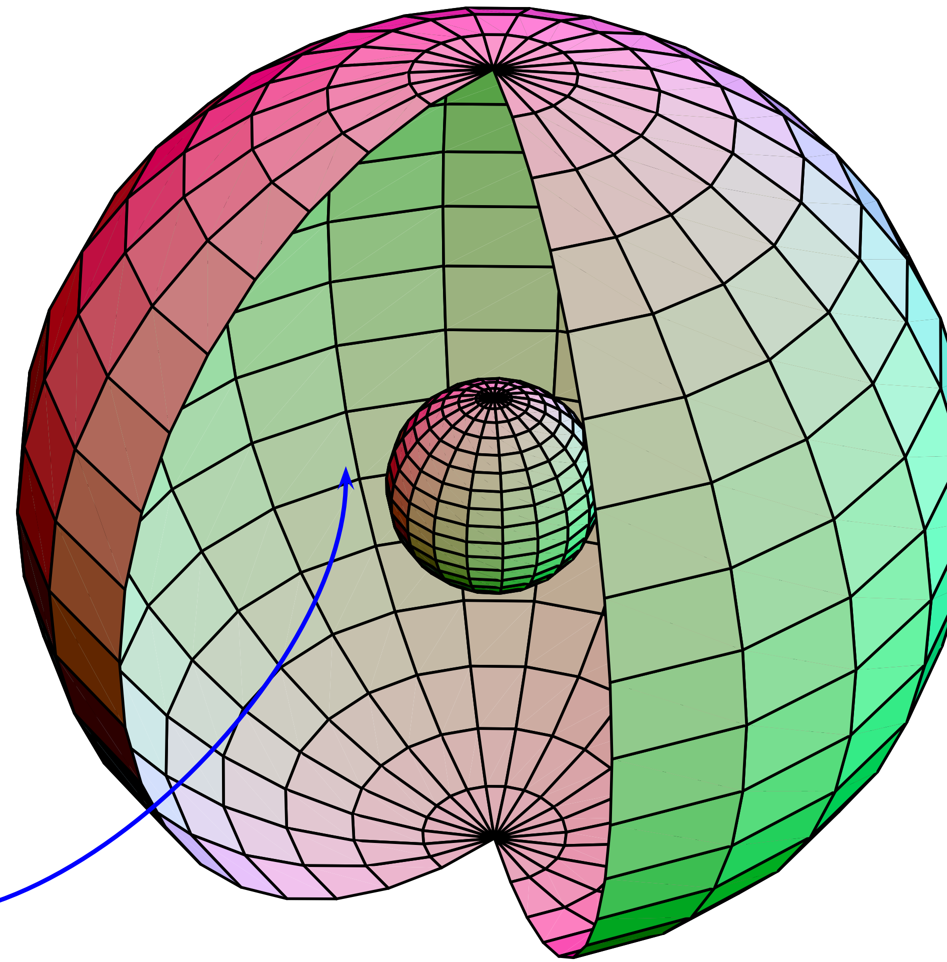
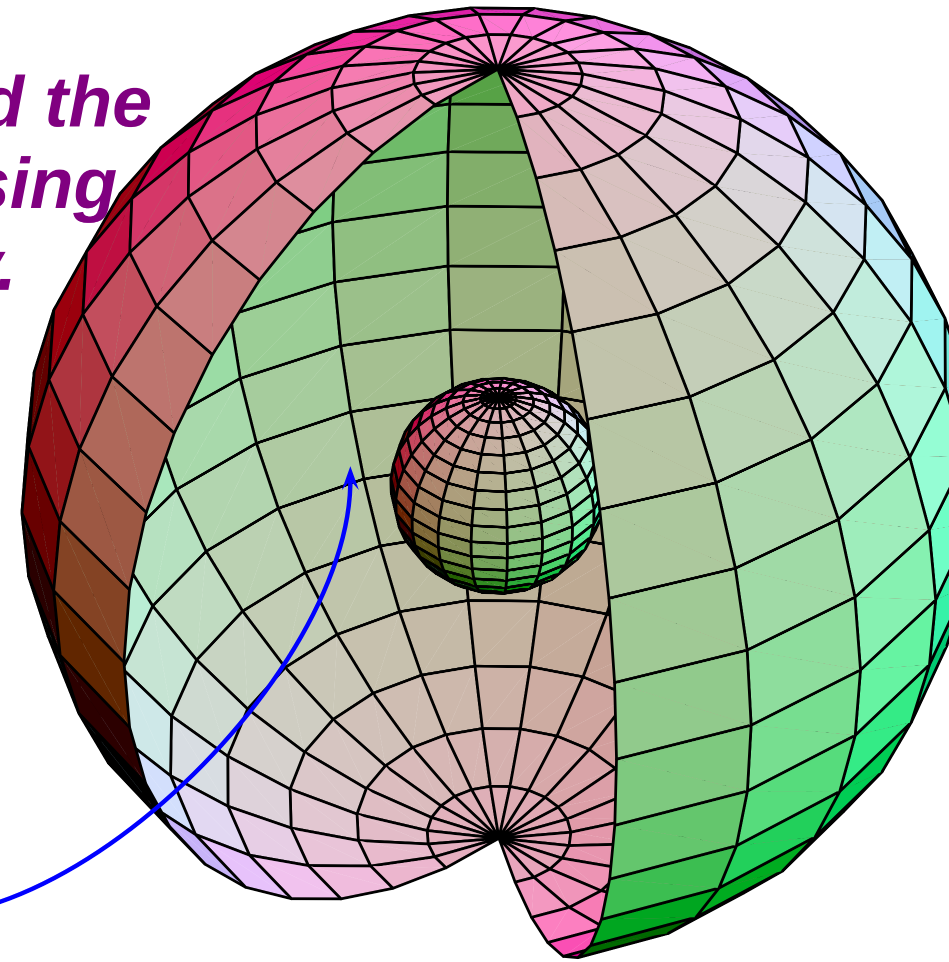


98% of the volume

What is the Intranucleon Interaction?

The question must be rigorously defined, and the answer mapped out using experiment and theory.



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QCD's Challenges

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Understand Emergent Phenomena

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- QCD – Complex behaviour

  arises from apparently simple rules

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- Is $^{12}\!C$ stable?
  - Probably not, if range range $\sim \dfrac{1}{2\, M_Q}$

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Is a unique long-range interaction between light-quarks responsible for all this or are there an uncountable infinity of qualitatively equivalent interactions?

Model QCD

Traditional approach to strong force problem

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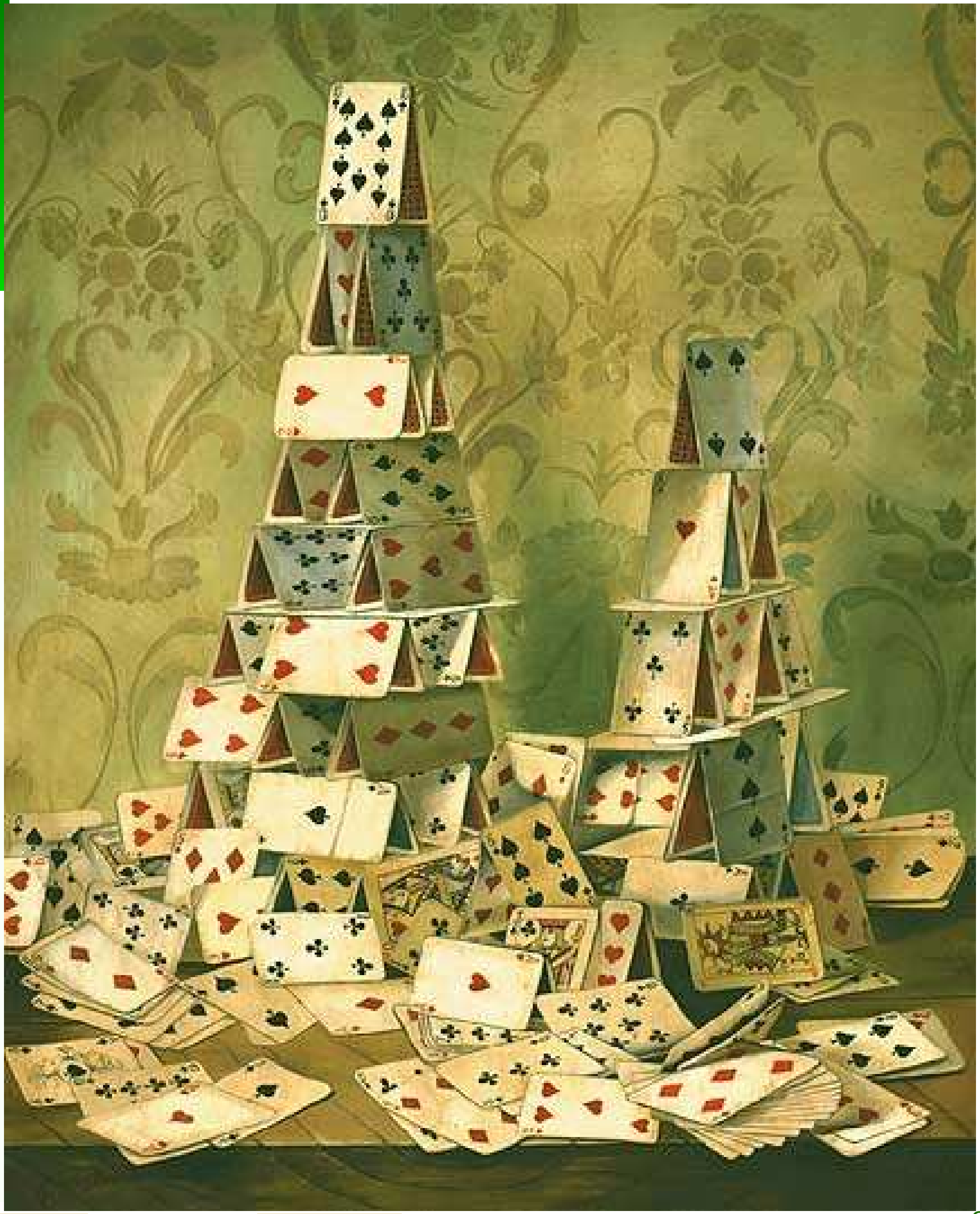

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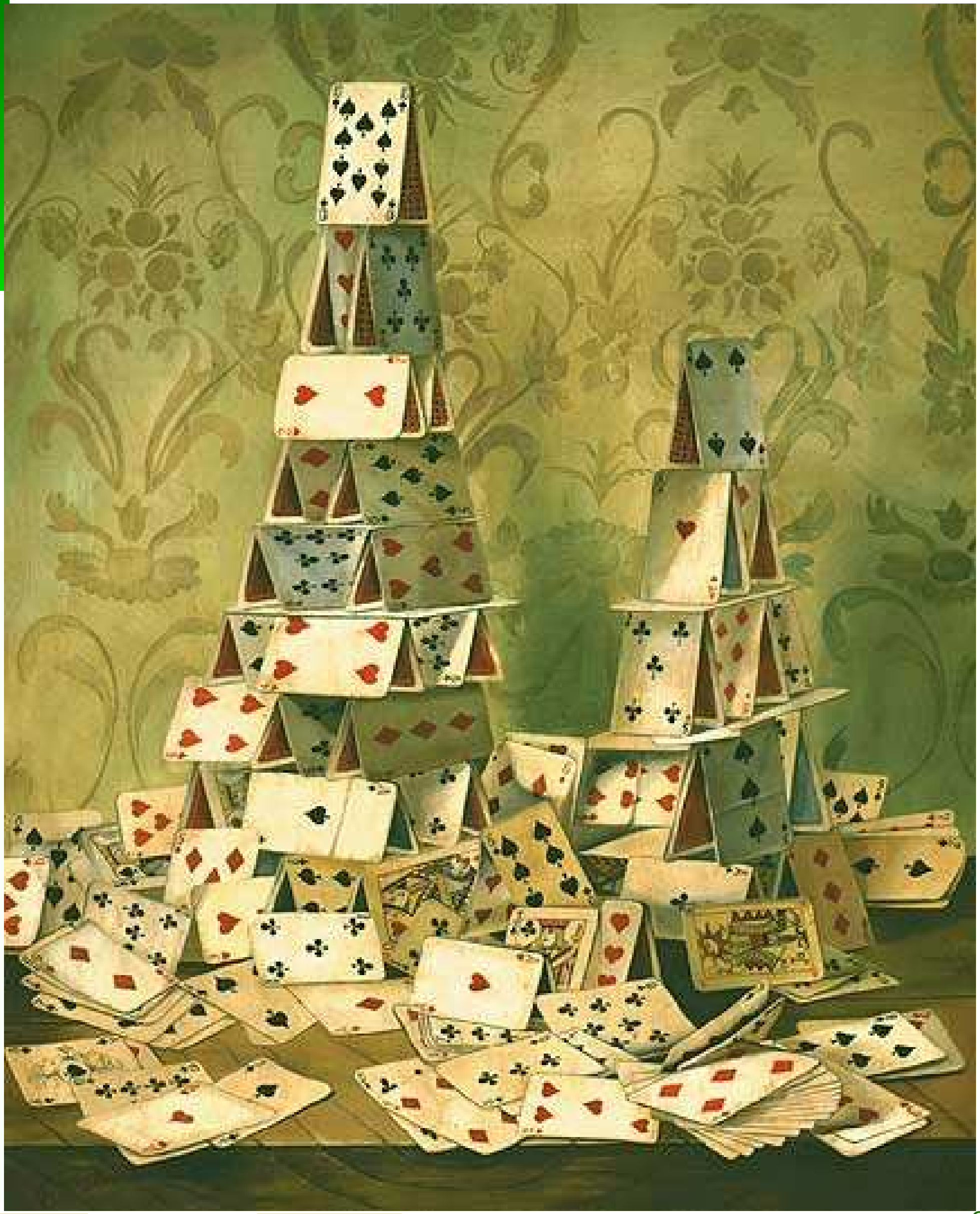

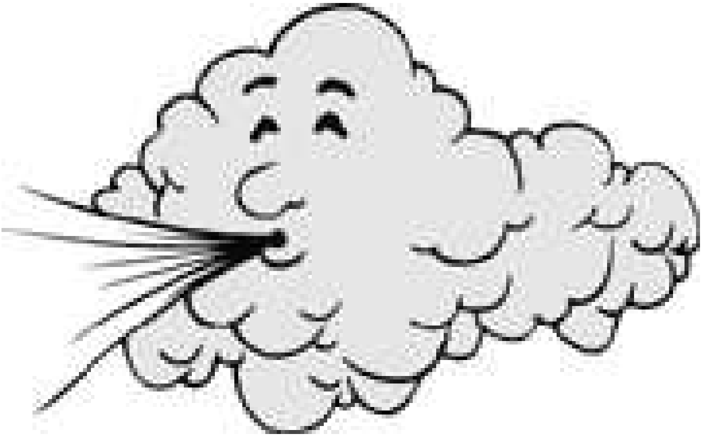

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Lattice QCD

One modern nonperturbative approach*Lattice QCD*

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A Compromise?
Dyson-Schwinger Equations

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- 1994 . . . “*As computer technology continues to improve, lattice gauge theory [LGT] will become an increasingly useful means of studying hadronic physics through investigations of discretised quantum chromodynamics [QCD]. . . . .*”

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- 1994 . . . "*However, it is equally important to develop other complementary nonperturbative methods based on continuum descriptions. In particular, with the advent of new accelerators such as CEBAF and RHIC, there is a need for the development of approximation techniques and models which bridge the gap between short-distance, perturbative QCD and the extensive amount of low- and intermediate-energy phenomenology in a single covariant framework. . . .*"

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Dyson-Schwinger Equations

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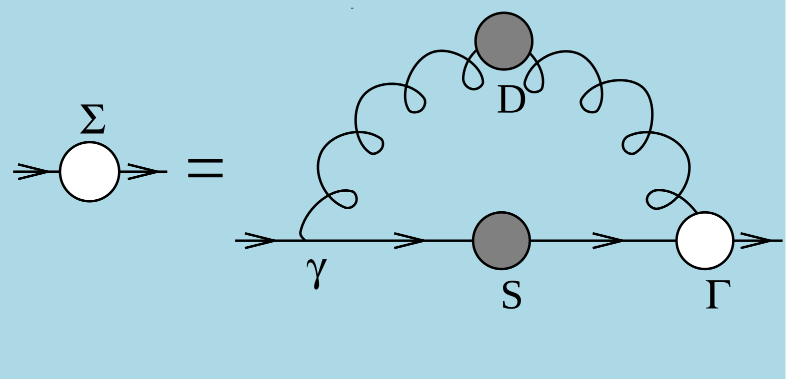

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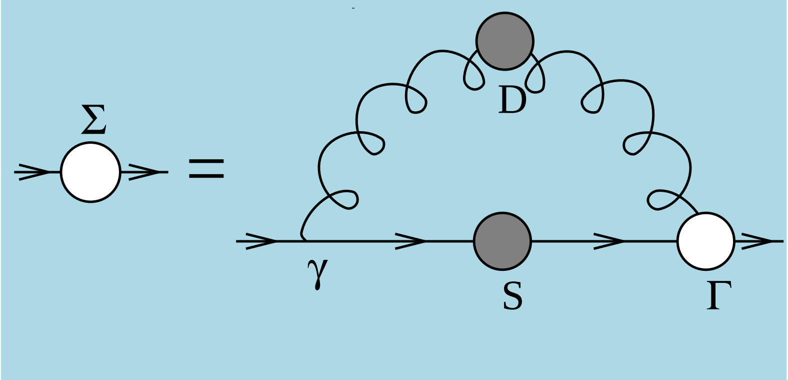

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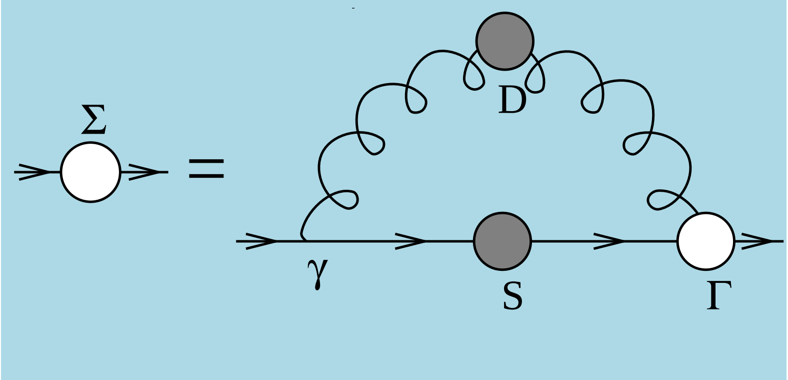

- These are nonperturbative equivalents in quantum field theory to the Lagrange equations of motion.
- Essential in simplifying the general proof of renormalisability of gauge field theories.

Dyson-Schwinger Equations

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Cross-Sections built from Schwinger Functions

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World . . .

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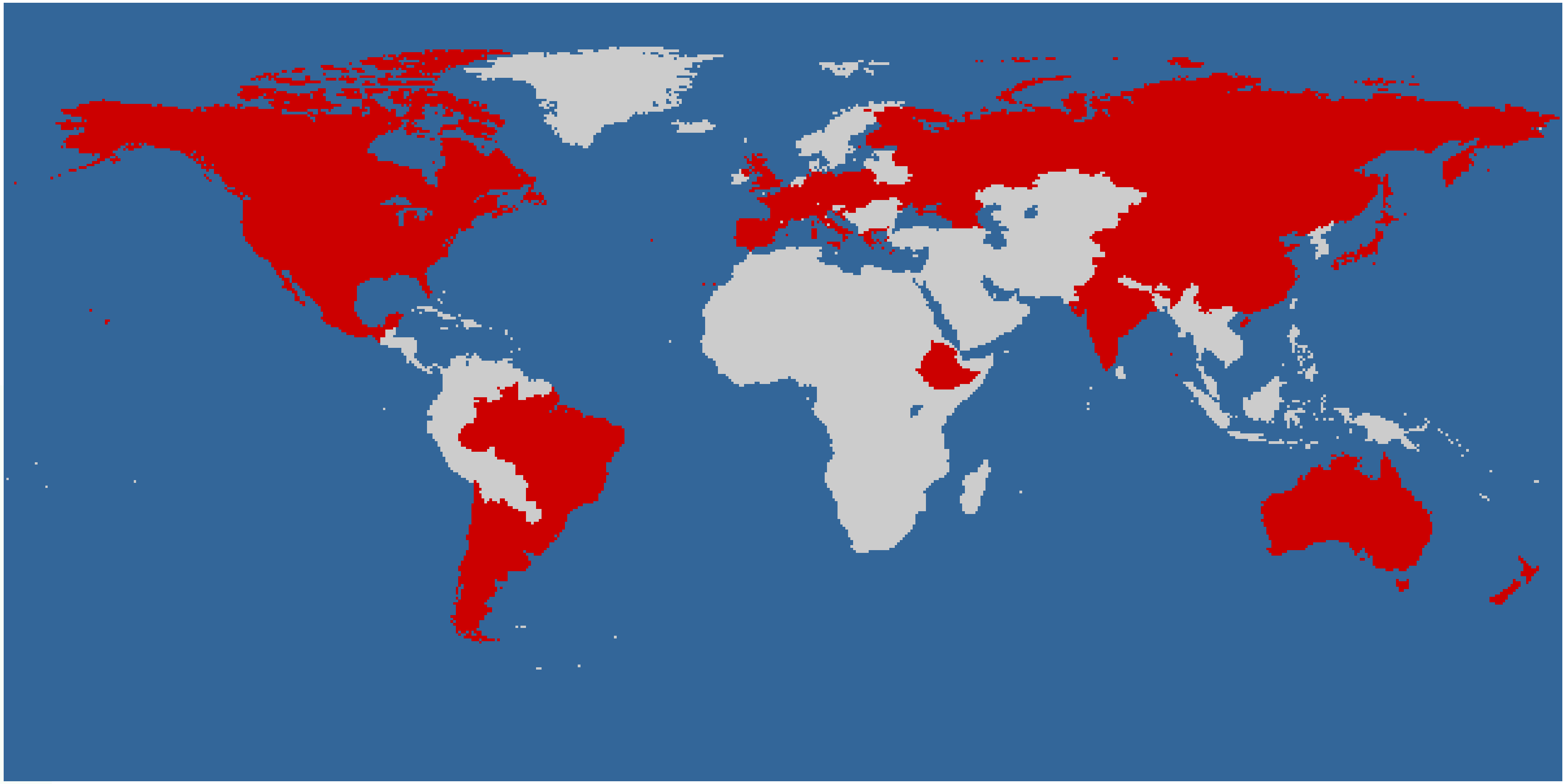
DSE Perspective



Persistent Challenge

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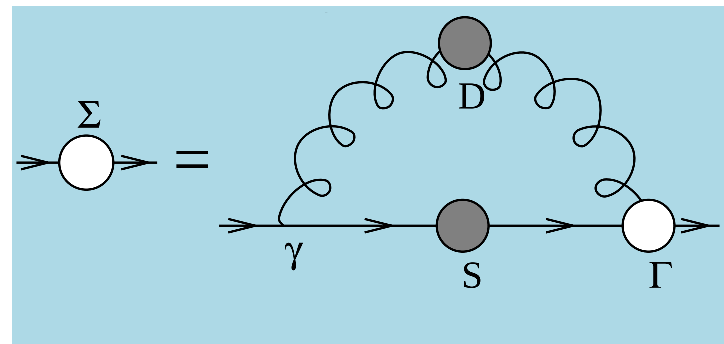

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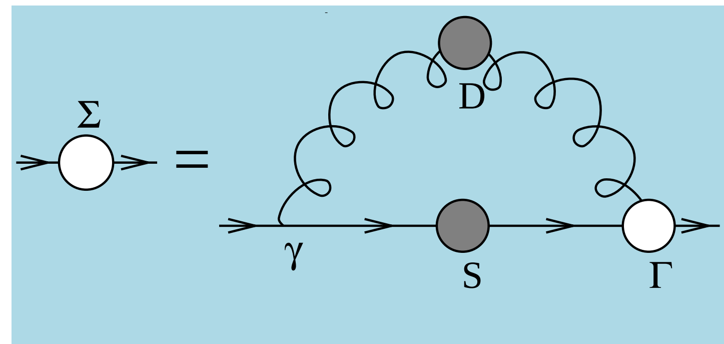

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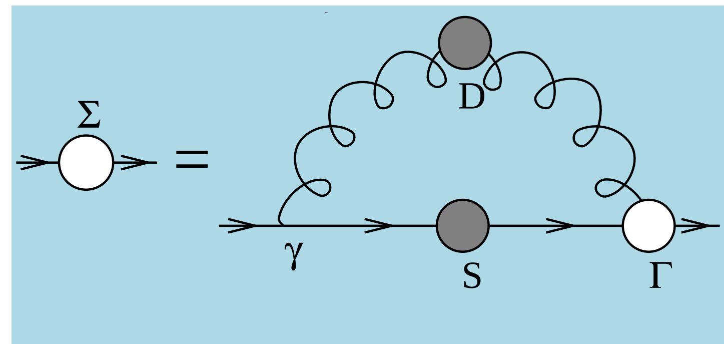

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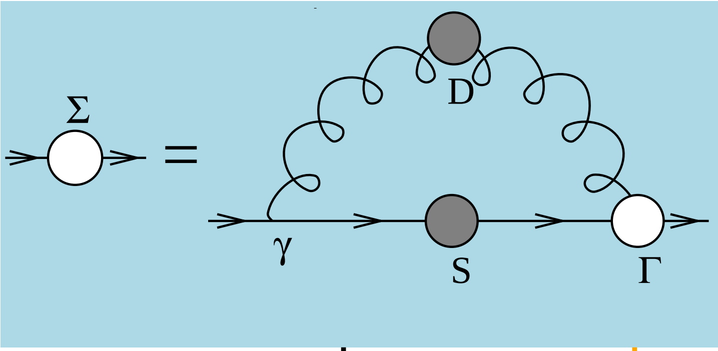

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    Not useful for the nonperturbative problems
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  H.J. Munczek Phys. Rev. D **52** (1995) 4736
  Dynamical chiral symmetry breaking, Goldstone's theorem and the consistency of the Schwinger-Dyson and Bethe-Salpeter Equations
  A. Bender, C. D. Roberts and L. von Smekal, Phys. Lett. B **380** (1996) 7
  Goldstone Theorem and Diquark Confinement Beyond Rainbow Ladder Approximation

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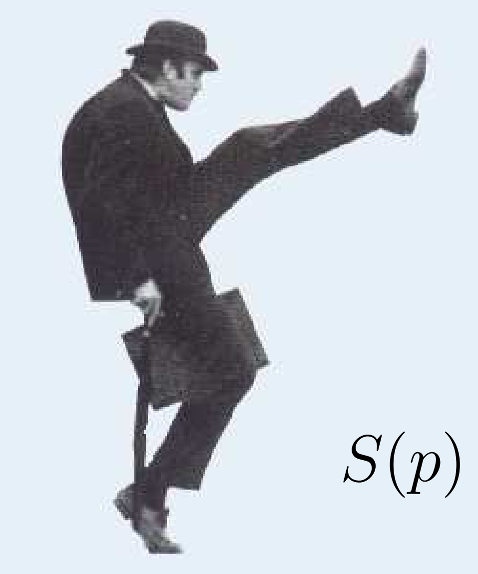
Perturbative Dressed-quark Propagator



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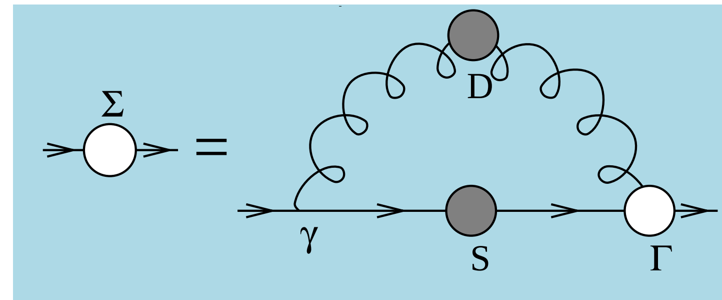
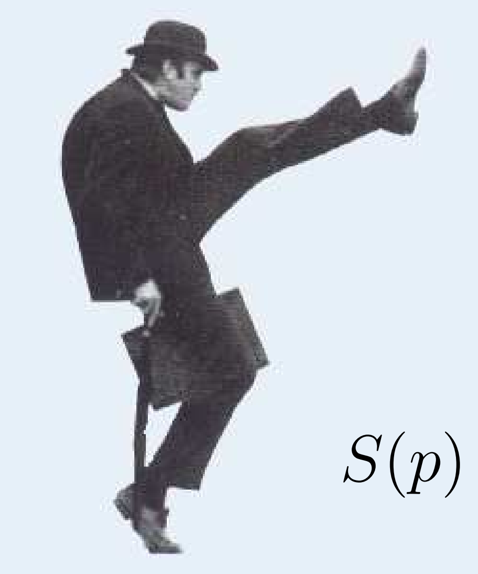
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



Gap Equation



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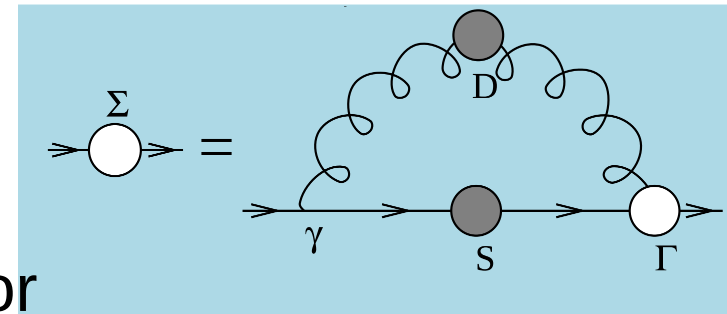

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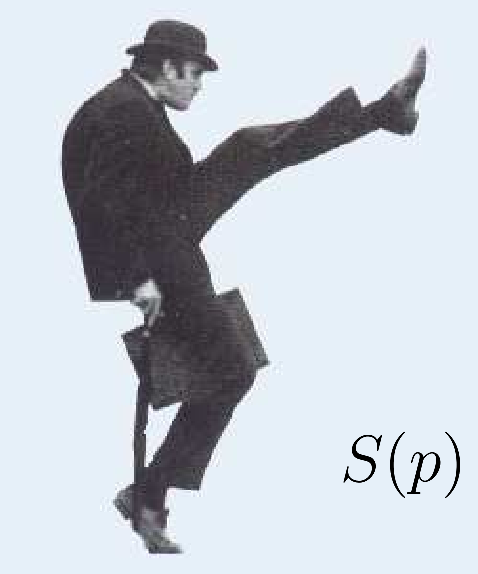

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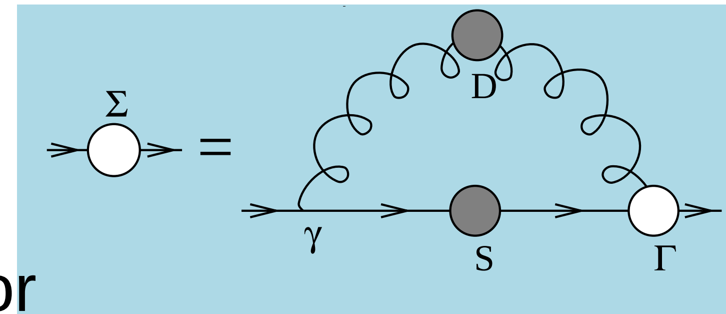

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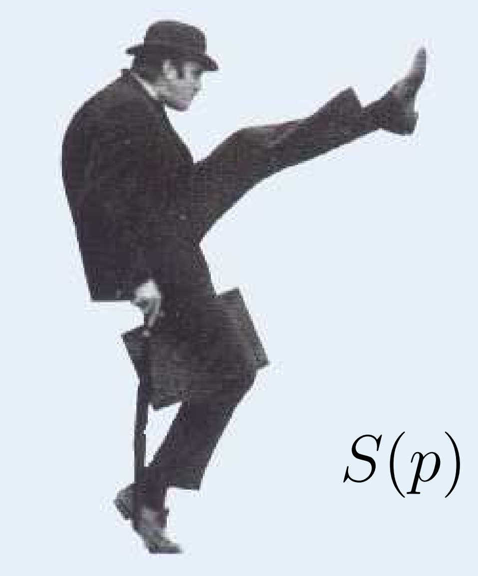
- Weak Coupling Expansion

  Reproduces Every Diagram in Perturbation Theory



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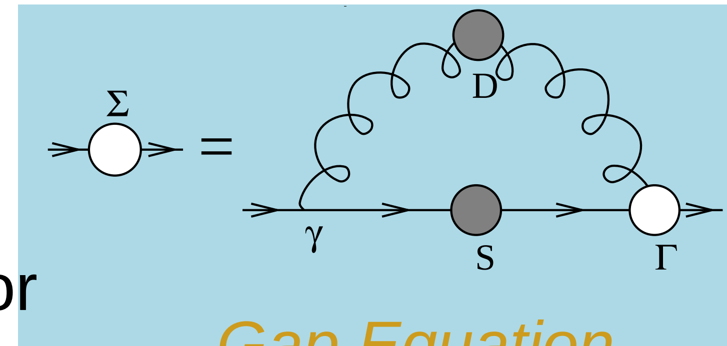

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  Reproduces Every Diagram in Perturbation Theory

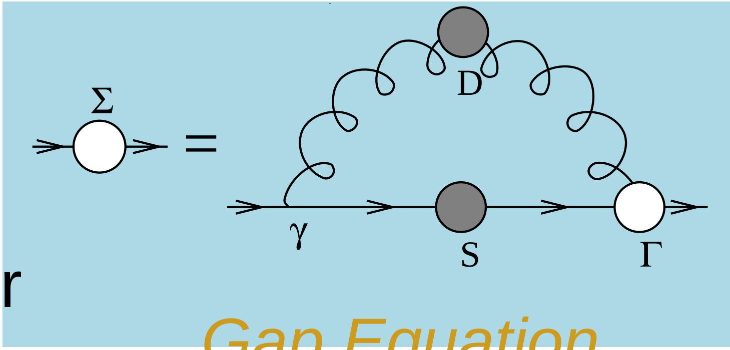
- But in Perturbation Theory

$$B(p^2) = m\left(1 - \frac{\alpha}{\pi}\ln\left[\frac{p^2}{m^2}\right] + \ldots\right) \stackrel{m\to 0}{\to} 0$$

Perturbative Dressed-quark Propagator

$$S(p) = \frac{Z(p^2)}{i\gamma\cdot p + M(p^2)}$$

- dressed-quark propagator



Gap Equation

$$S(p) = \frac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$$

No DCSB Here!

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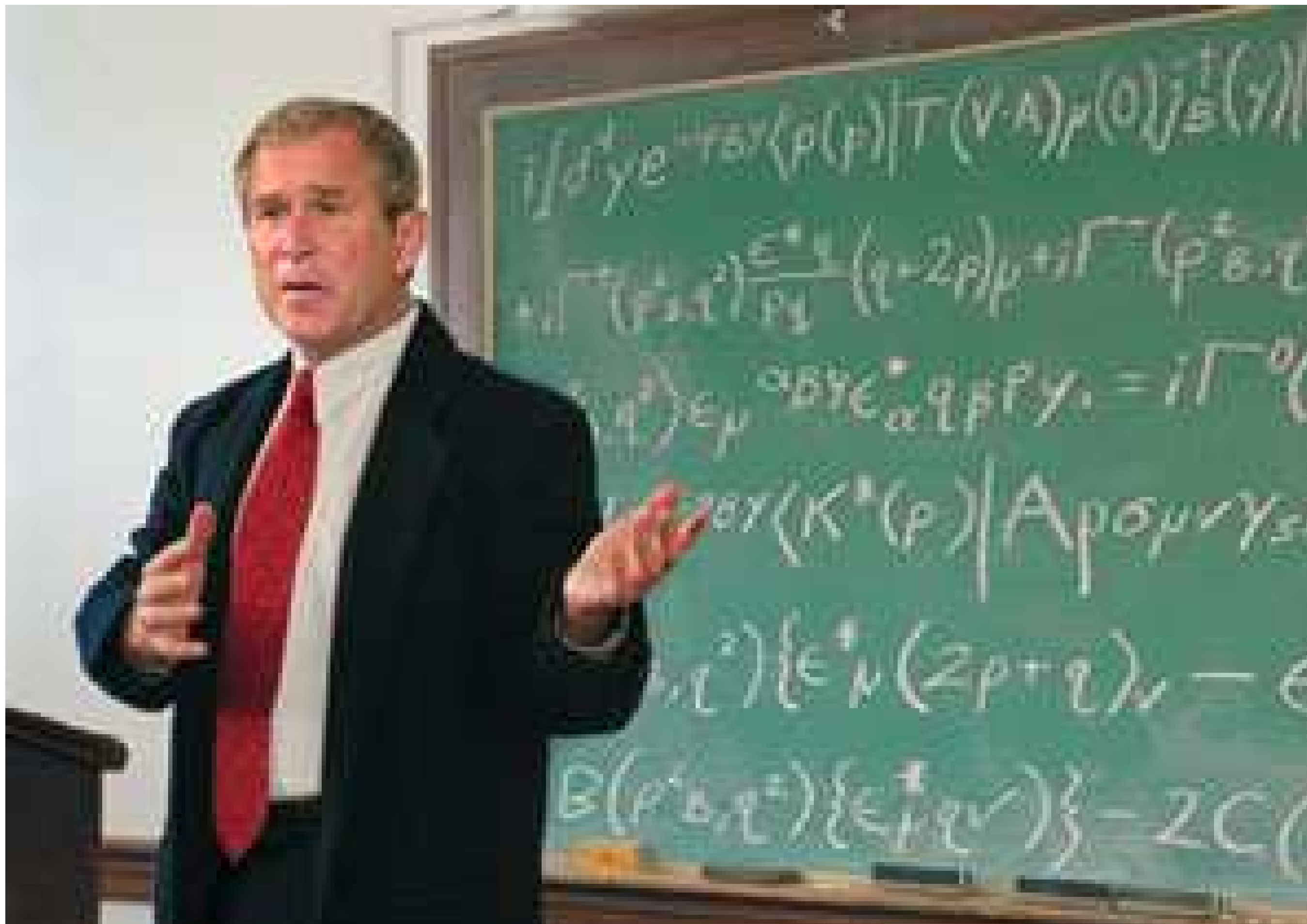
Explanation?



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Dressed-Quark Propagator

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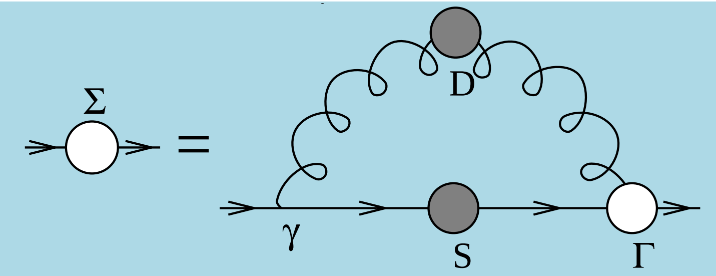

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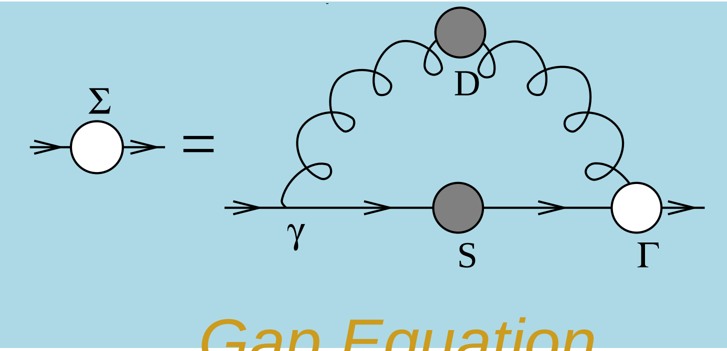
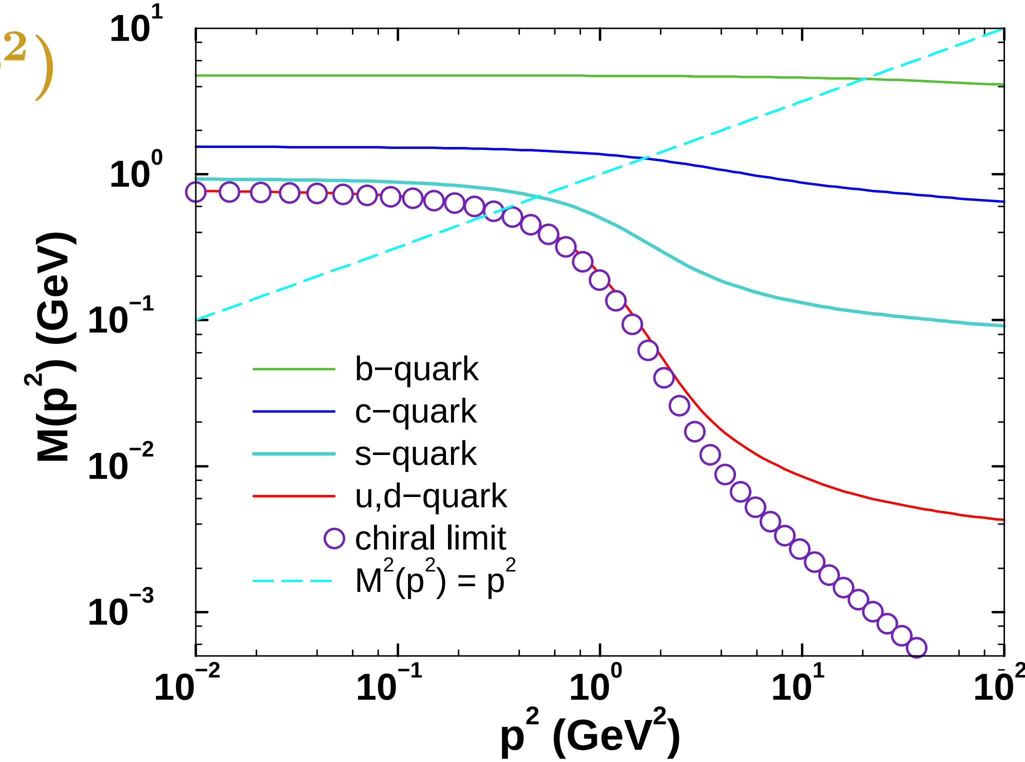


Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

$\Rightarrow$ IR Enhancement of $M(p^2)$



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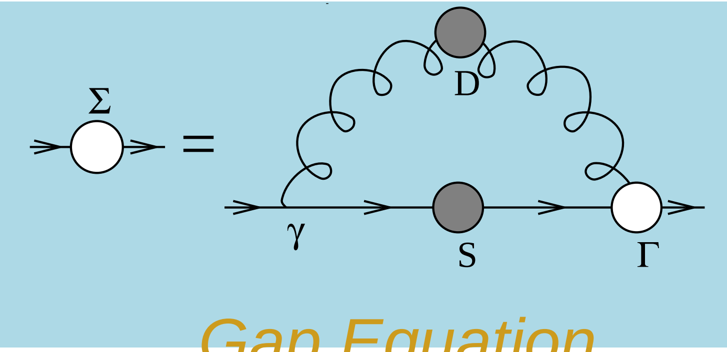

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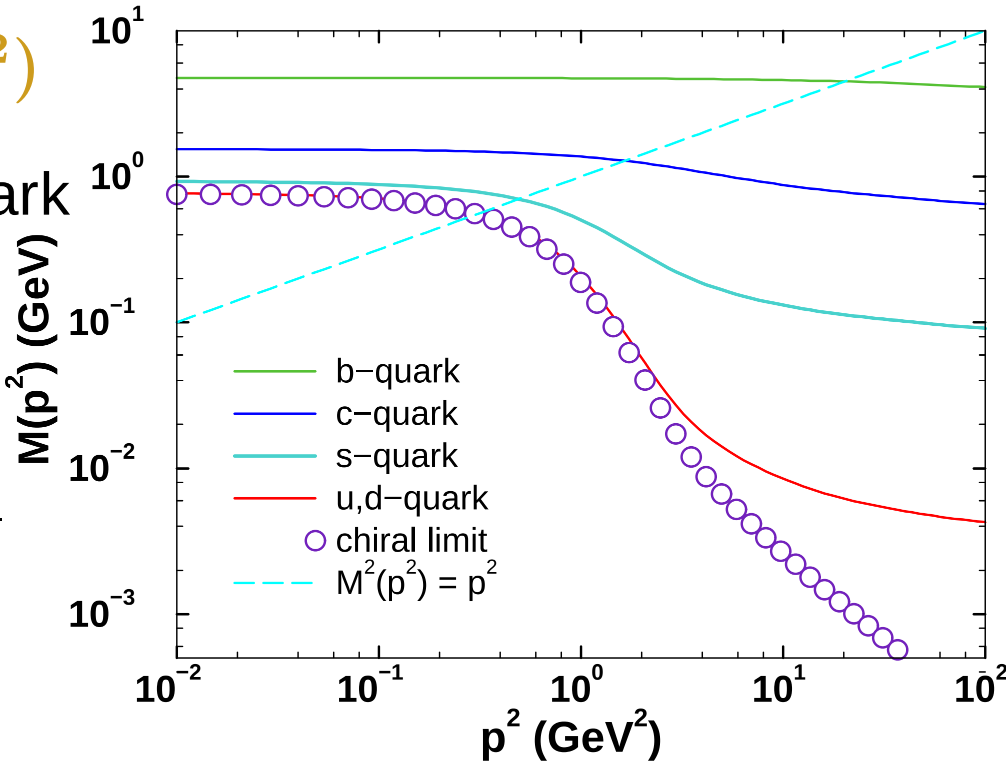
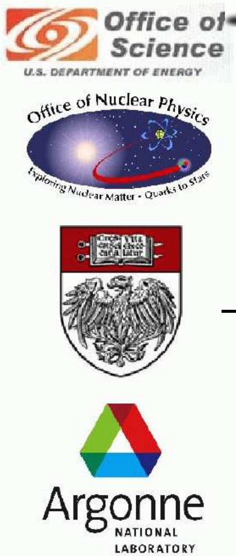
- Euclidean Constituent–Quark Mass: M_f^E: $p^2 = M(p^2)^2$

flavour	u/d	s	c	b
$\frac{M^E}{m_\zeta}$	$\sim 10^2$	~ 10	~ 1.5	~ 1.1





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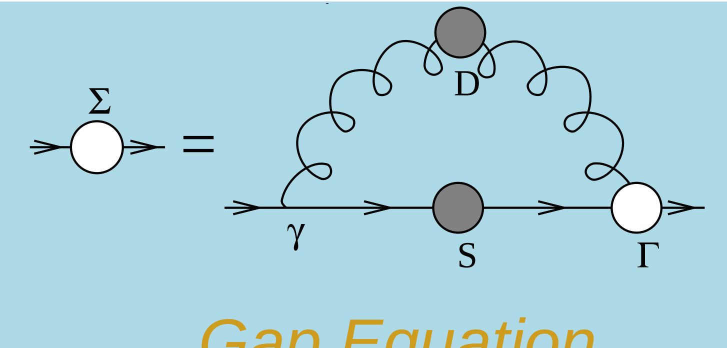

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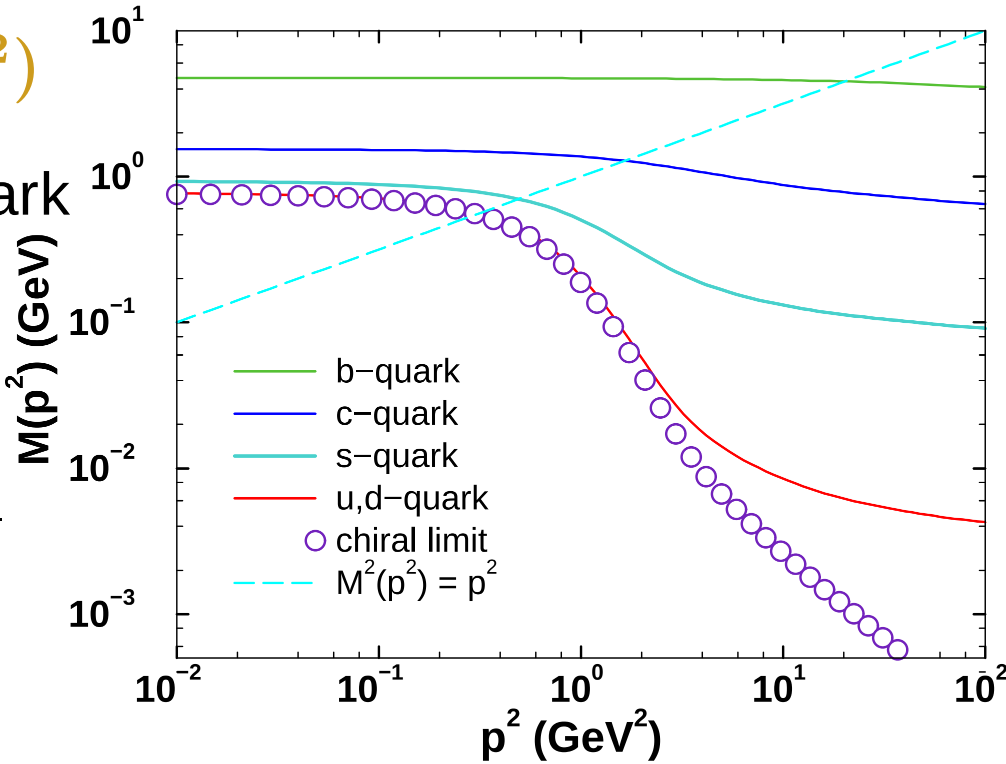

Predictions confirmed in numerical simulations of lattice-QCD

Dressed-Quark Propagator

- Longstanding Prediction of Dyson-Schwinger Equation Studies

Dressed-Quark Propagator

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  - E.g., *Dyson-Schwinger equations and their application to hadronic physics*,
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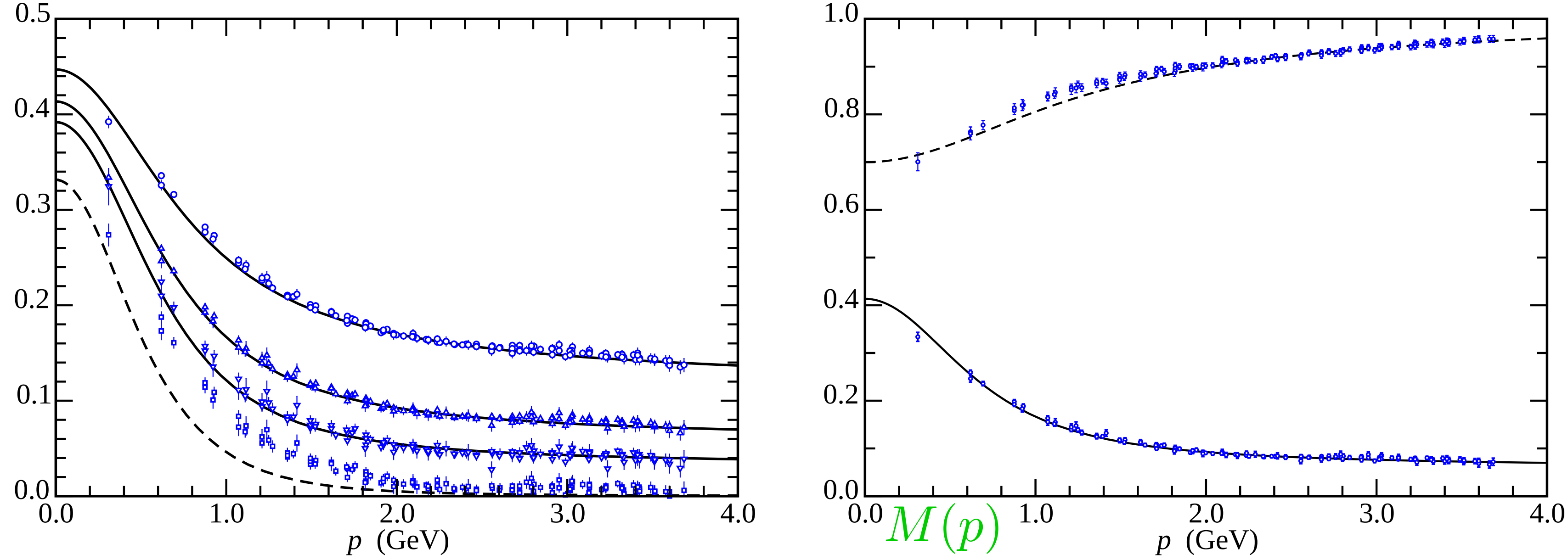
Quenched-QCD Dressed-Quark Propagator

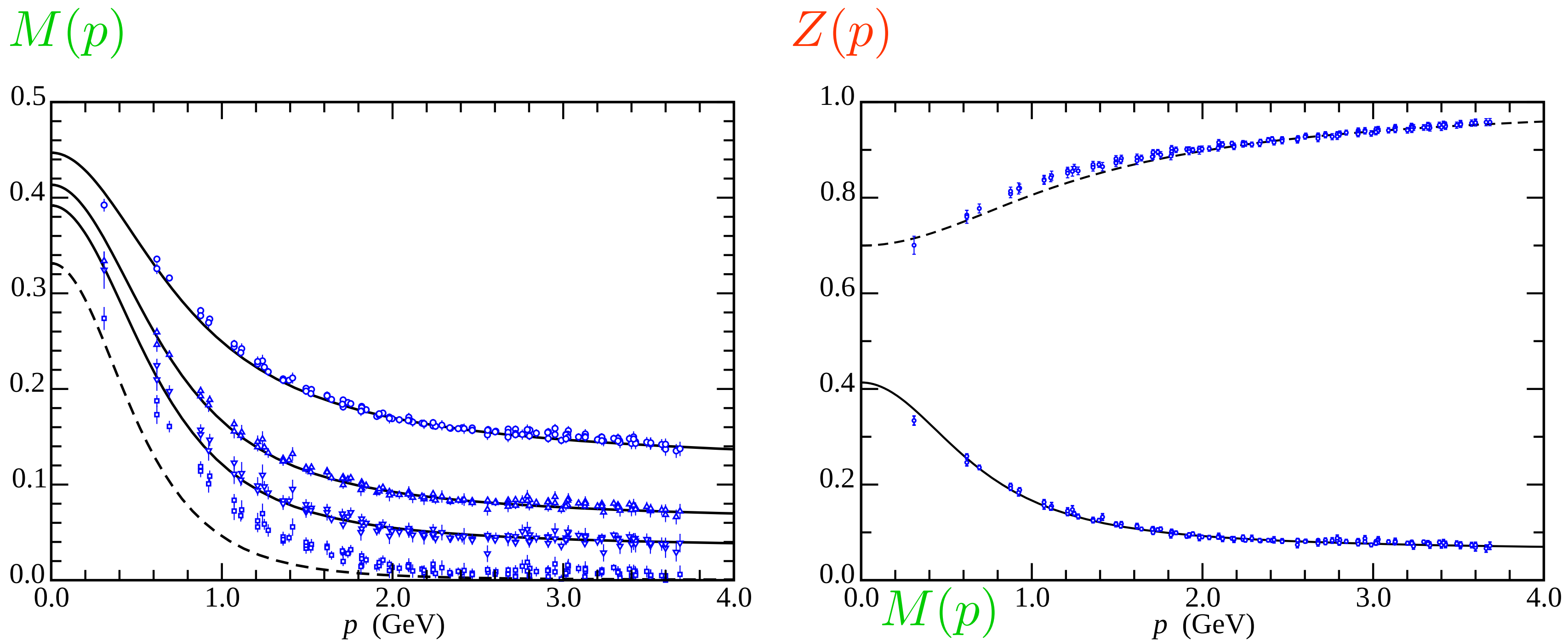
$M(p)$ $Z(p)$



$M(p)$

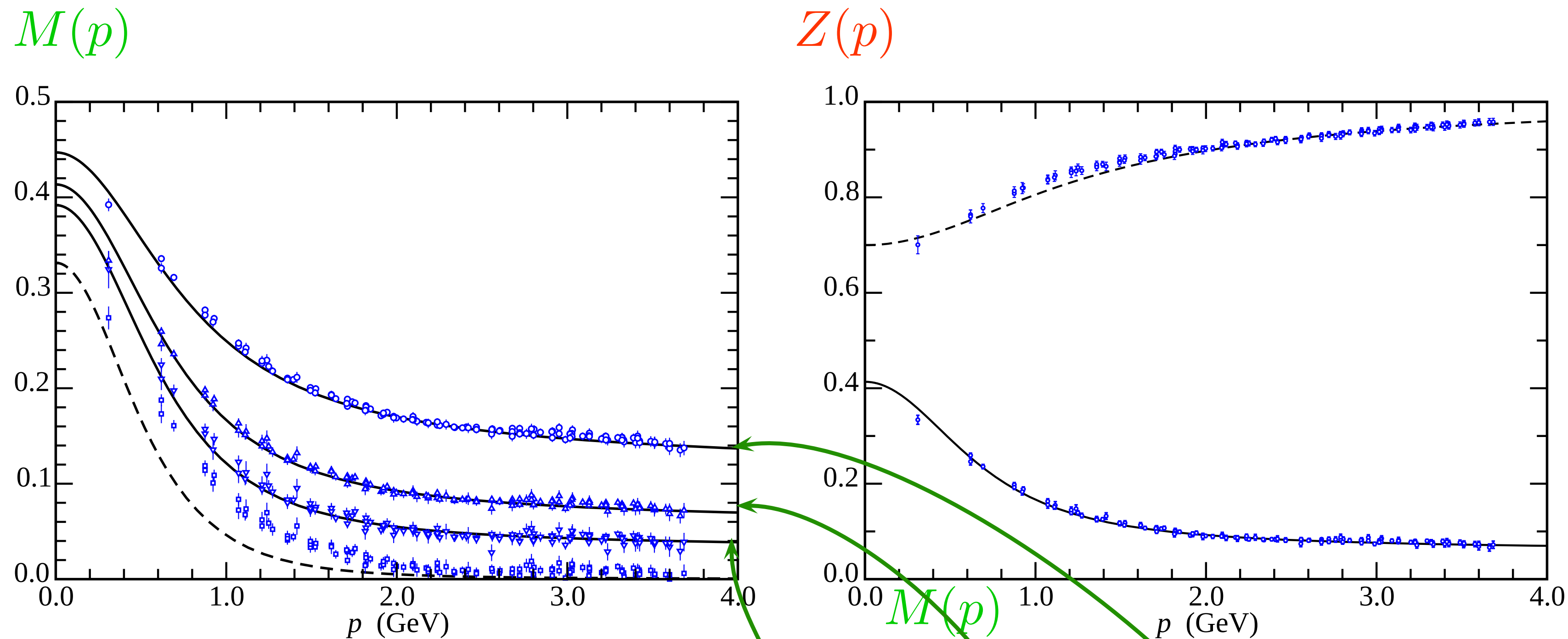
Quenched-QCD Dressed-Quark Propagator

2002



- "*data*:" Quenched Lattice Meas.
  – Bowman, Heller, Leinweber, Williams: he-lat/0209129

2002 Quenched-QCD Dressed-Quark Propagator



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Quenched-QCD Dressed-Quark Propagator

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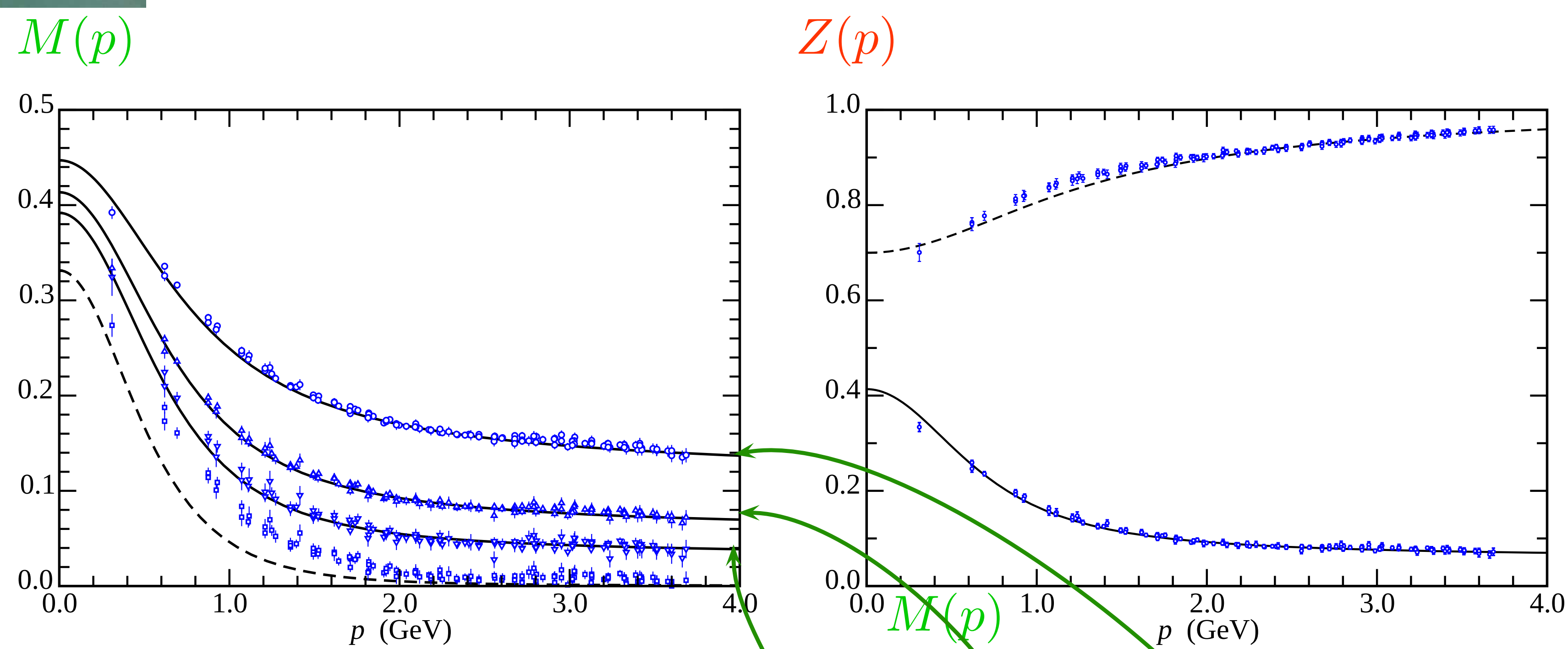

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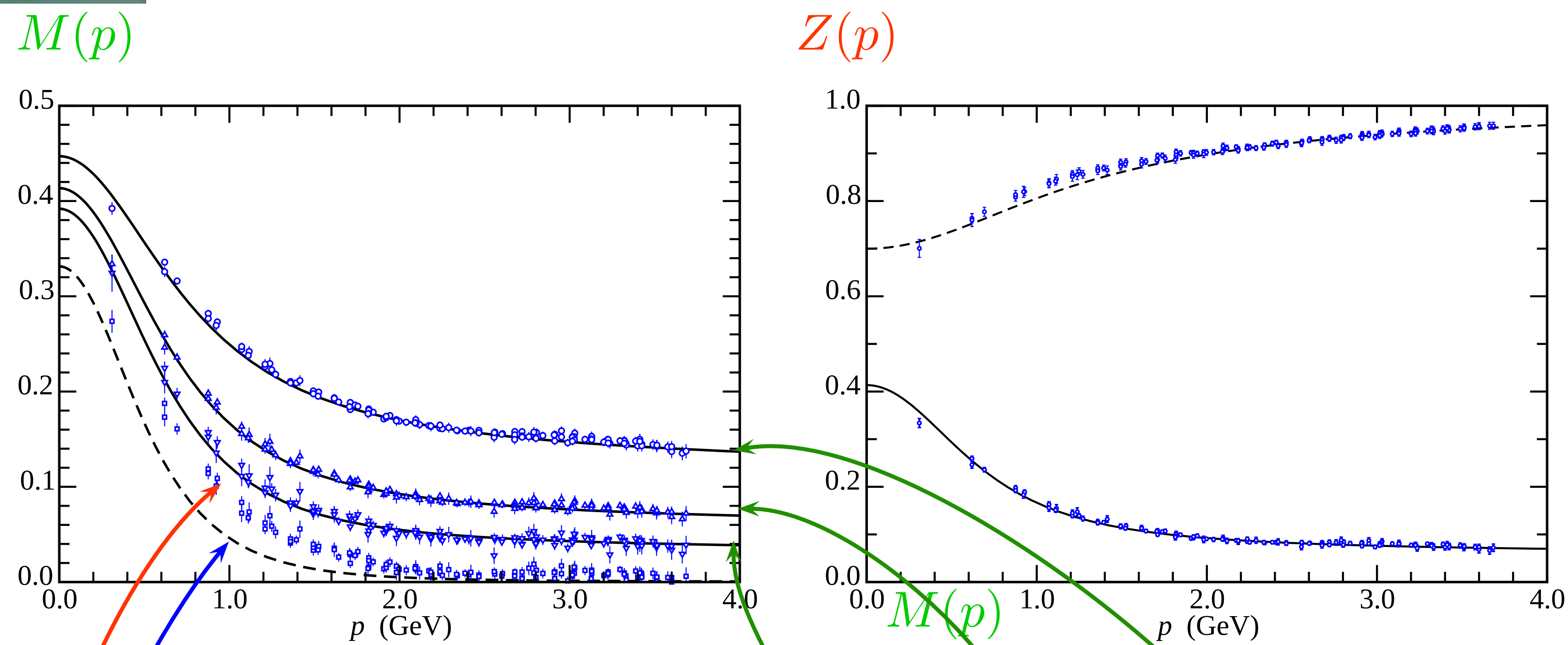
Quenched-QCD Dressed-Quark Propagator



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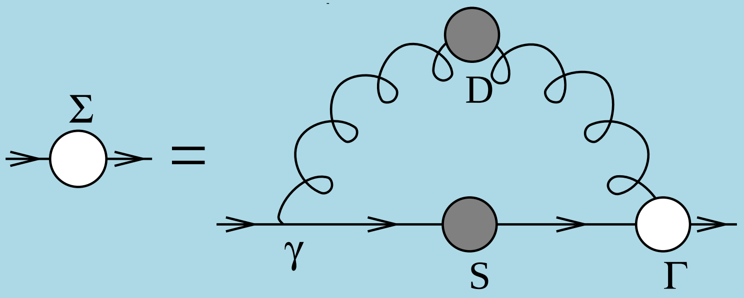
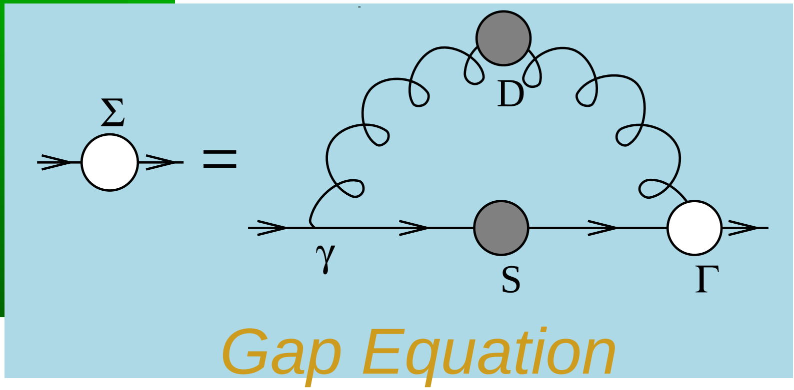
- Linear extrapolation of lattice data to chiral limit is inaccurate

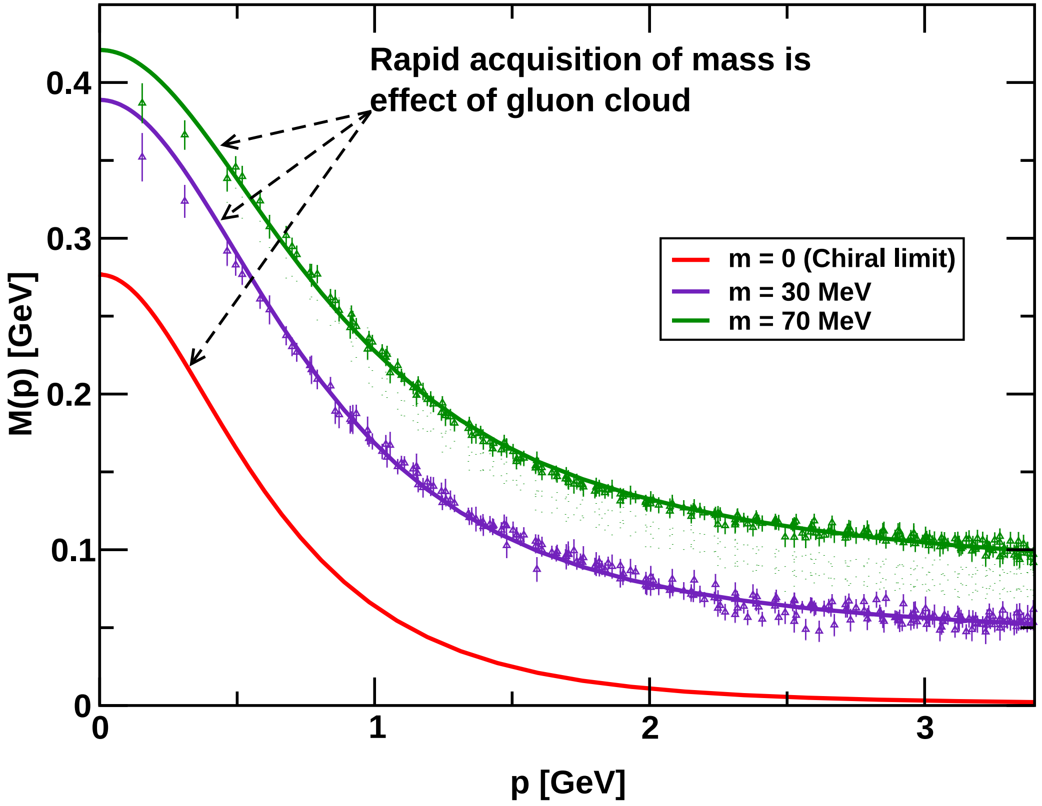
Frontiers of Nuclear Science: A Long Range Plan (2007)



Gap Equation

Frontiers of Nuclear Science: Theoretical Advances





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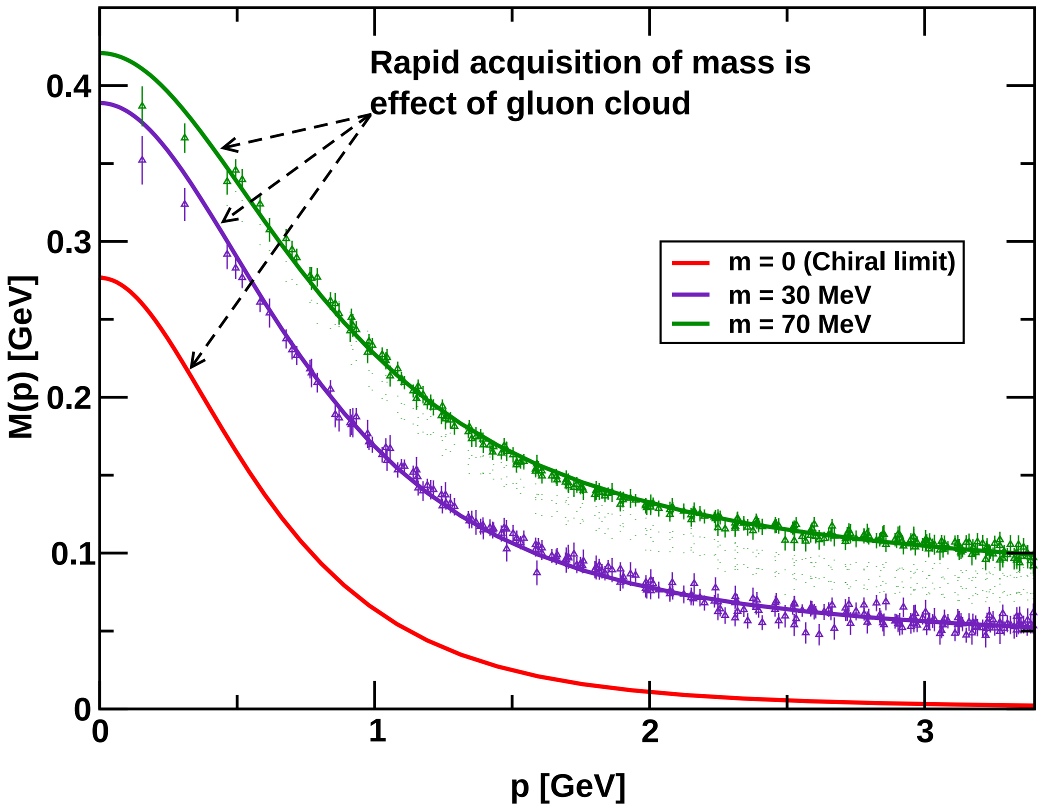
Mass from nothing.

In QCD a quark's effective mass depends on its momentum. The function describing this can be calculated and is depicted here. Numerical simulations of lattice QCD (data, at two different bare masses) have confirmed model predictions (solid curves) that the vast bulk of the constituent mass of a light quark comes from a cloud of gluons that are dragged along by the quark as it propagates. In this way, a quark that appears to be absolutely massless at high energies ($m = 0$, red curve) acquires a large constituent mass at low energies.



Hadrons

- Established understanding of two- and three-point functions

Hadrons

- Established understanding
  of two- and three-point functions
- What about bound states?

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Hadrons

- Without bound states,
  Comparison with experiment is
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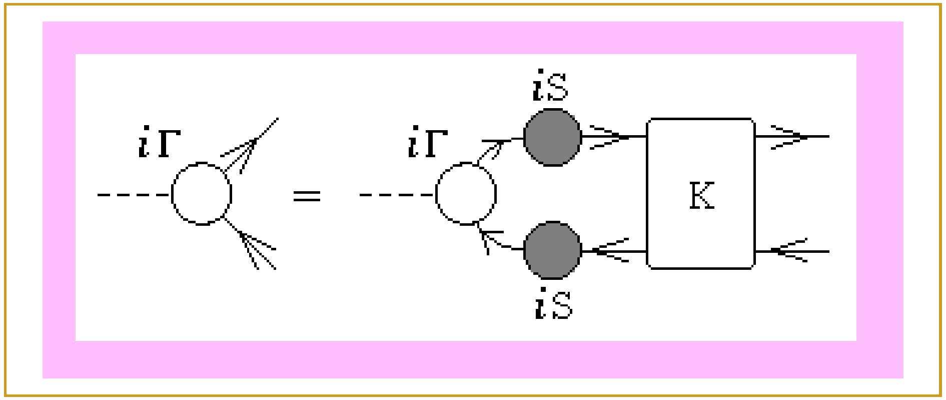
- Without bound states, Comparison with experiment is impossible
- They appear as pole contributions to $n \geq 3$-point colour-singlet Schwinger functions

- Without bound states, Comparison with experiment is impossible
- Bethe-Salpeter Equation



QFT Generalisation of Lippmann-Schwinger Equation.

- Without bound states,
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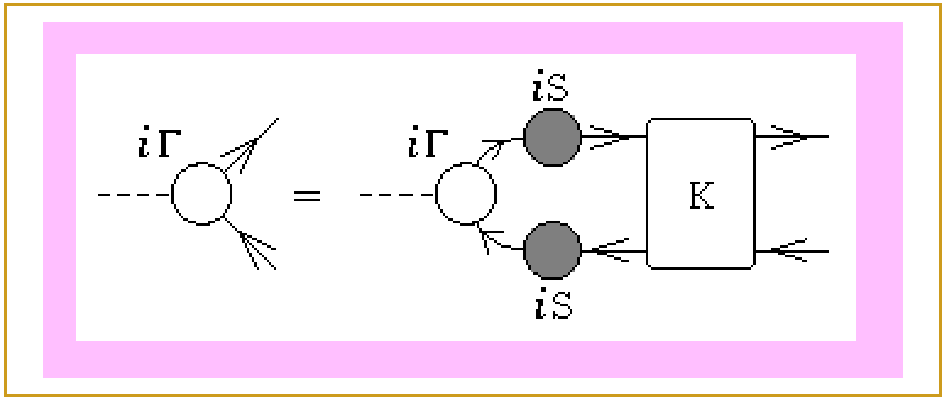

QFT Generalisation of Lippmann-Schwinger Equation.

- What is the kernel, K?

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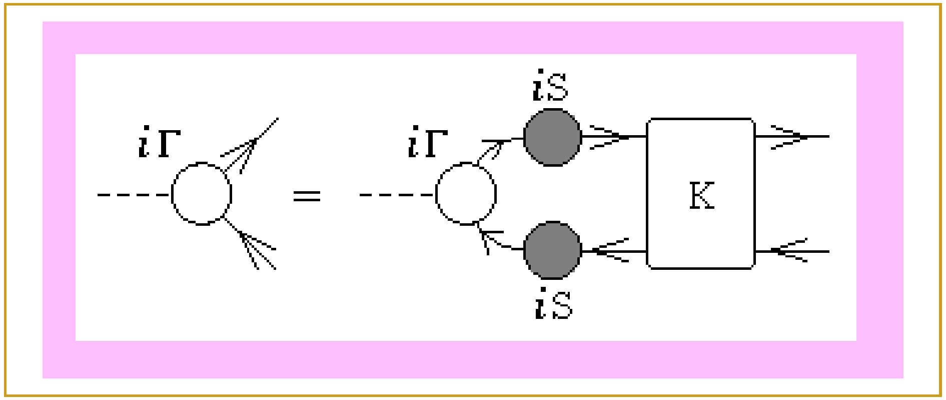

QFT Generalisation of Lippmann-Schwinger Equation.

- What is the kernel, K?

or

What is the light-quark Long-Range Potential?

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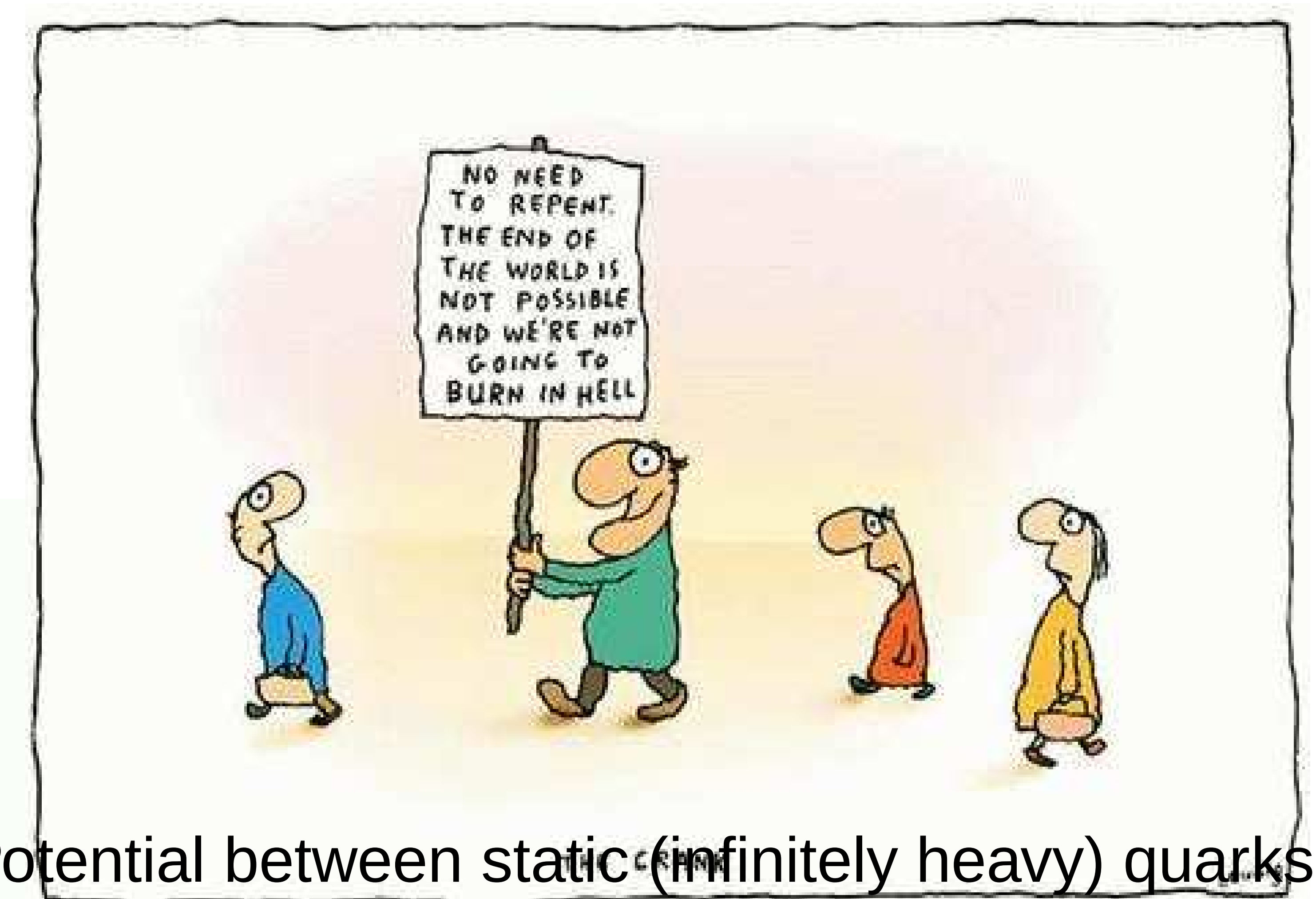
What is the light-quark Long-Range Potential?



Potential between static (infinitely heavy) quarks measured in numerical simulations of lattice-QCD ***is not related*** in any simple way to the light-quark interaction.

Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

$$P_\mu \; \Gamma^l_{5\mu}(k;P) \quad = \quad \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5 \;\; \mathcal{S}^{-1}(k_-)$$

$$-M_\zeta \, i\Gamma^l_5(k;P) - i\Gamma^l_5(k;P)\, M_\zeta$$

QFT Statement of Chiral Symmetry

Bethe-Salpeter Kernel

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Kernels very different

but must be intimately related

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Satisfies BSE   Satisfies DSE

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- Nontrivial constraint

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Satisfies BSE

Satisfies DSE

Kernels very different

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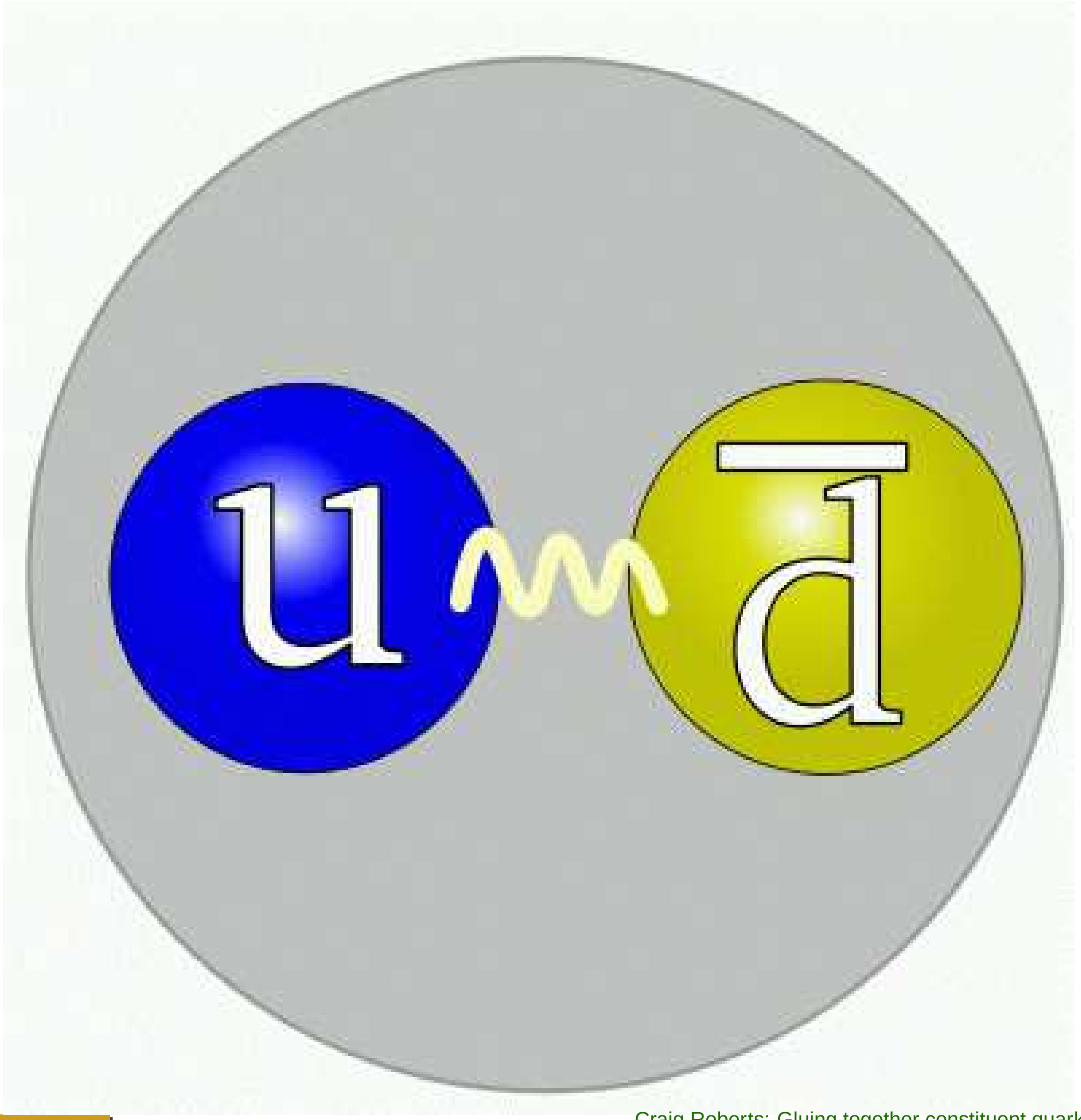
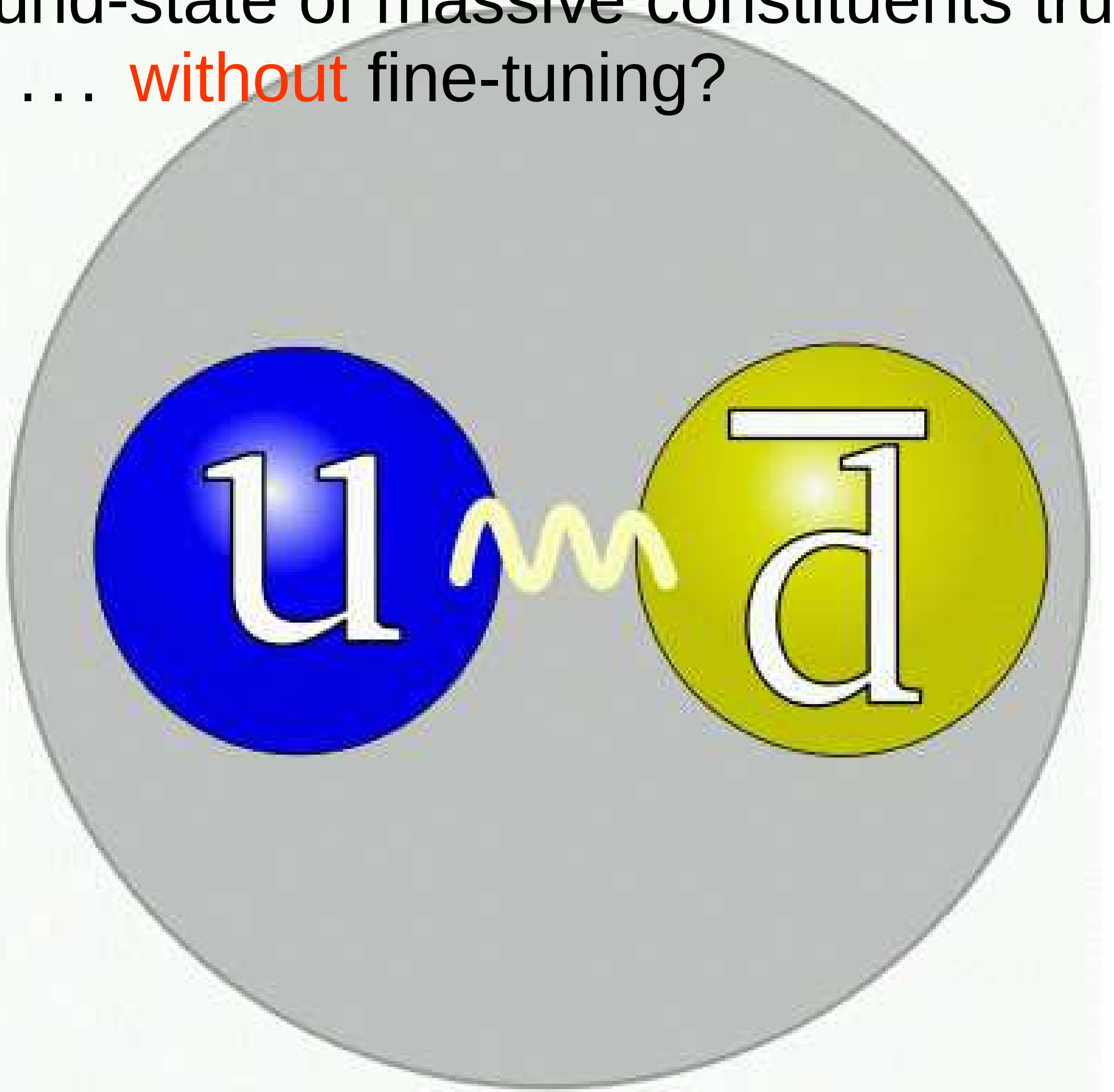
- Relation must be preserved by truncation
- Failure $\Rightarrow$ Explicit Violation of QCD's Chiral Symmetry

Pion and . . .
Pseudoscalar Mesons?



Pseudoscalar Mesons?

Can a bound-state of massive constituents truly be massless . . . without fine-tuning?



Radial Excitations & Chiral Symmetry

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Radial Excitations & Chiral Symmetry

$$\boxed{f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H}$$

Radial Excitations & Chiral Symmetry

(Maris, Roberts, Tandy nu-th/9707003)

$$\boxed{f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H}$$

- Mass^2 of pseudoscalar hadron

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Radial Excitations & Chiral Symmetry

$$\boxed{f_H \;\; m_H^2 = - \;\; \rho_\zeta^H \;\; \mathcal{M}_H}$$

$$\mathcal{M}_H := \mathrm{tr}_{\mathrm{flavour}}\left[M_{(\mu)}\left\{T^H, \left(T^H\right)^{\mathrm{t}}\right\}\right] = m_{q_1} + m_{q_2}$$

- Sum of constituents' current-quark masses
- e.g., $T^{K^+} = \frac{1}{2}\left(\lambda^4 + i\lambda^5\right)$

(Maris, Roberts, Tandy
nu-th/9707003)

$$\boxed{f_H \, m_H^2 = - \; \rho_\zeta^H \;\; \mathcal{M}_H}$$

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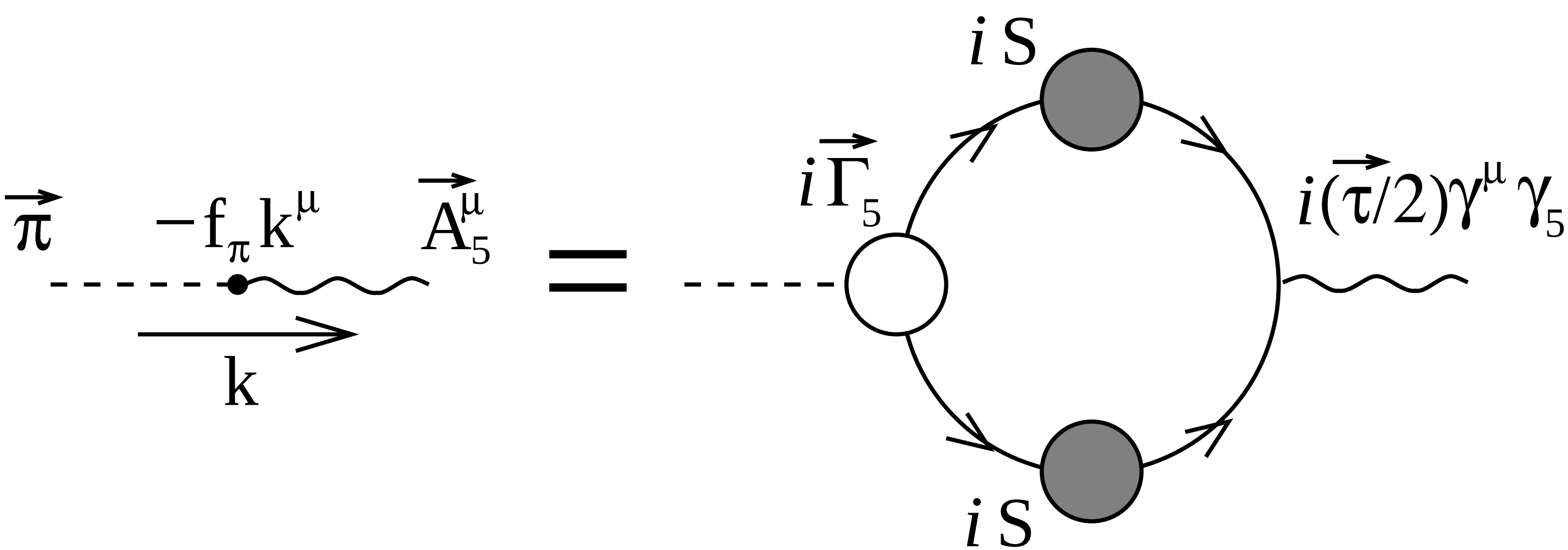
- Pseudovector projection of BS wave function at $x = 0$
- Pseudoscalar meson's leptonic decay constant



Radial Excitations & Chiral Symmetry

(Maris, Roberts, Tandy nu-th/9707003)

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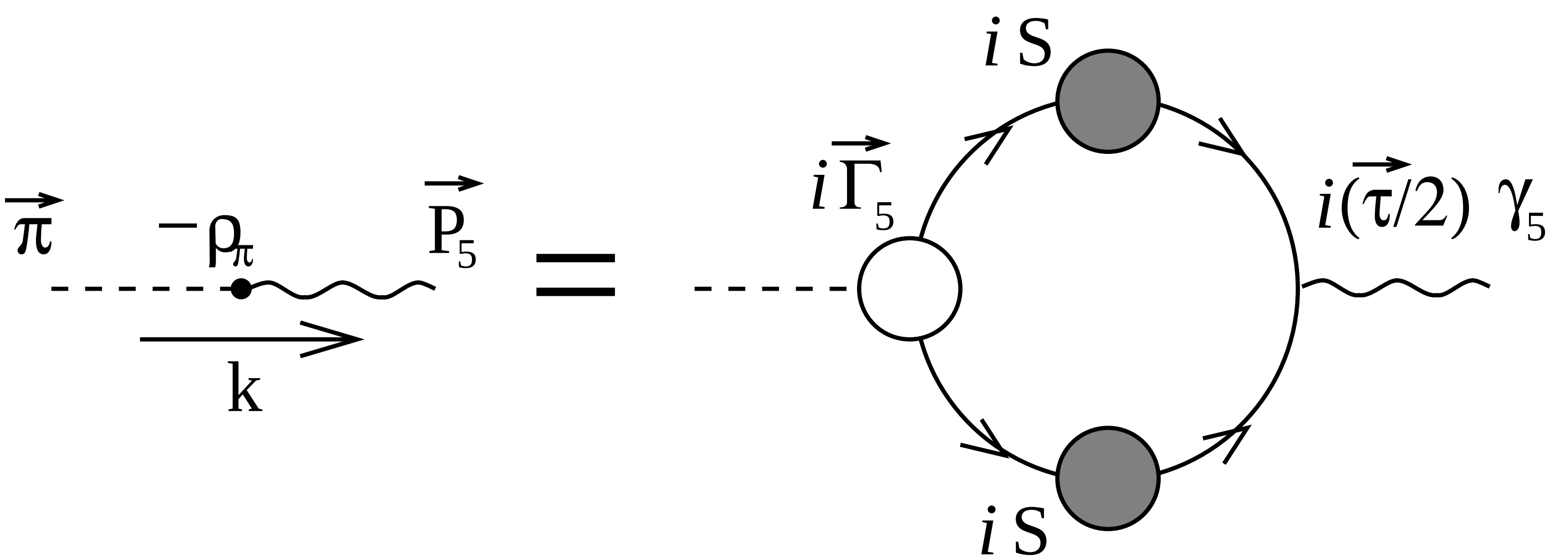

Radial Excitations & Chiral Symmetry

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- Light-quarks; i.e., $m_q \sim 0$
  - $f_H \to f_H^0$ & $\rho_\zeta^H \to \frac{-\langle \bar{q}q\rangle_\zeta^0}{f_H^0}$, Independent of m_q

Hence $\boxed{m_H^2 = \frac{-\langle \bar{q}q\rangle_\zeta^0}{(f_H^0)^2}\, m_q}$ . . . GMOR relation, a corollary

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  Hence $\boxed{m_H^2 = \dfrac{-\langle \bar{q}q \rangle_\zeta^0}{(f_H^0)^2}\, m_q}$ ...GMOR relation, a corollary

- Heavy-quark + light-quark

  $\Rightarrow f_H \propto \dfrac{1}{\sqrt{m_H}}$ and $\rho_\zeta^H \propto \sqrt{m_H}$

  Hence, $\boxed{m_H \propto m_q}$

  ... QCD Proof of Potential Model result

Radial Excitations & Chiral Symmetry

Höll, Krassnigg, Roberts
nu-th/0406030

$$f_H \; m_H^2 = - \; \rho_\zeta^H \; \mathcal{M}_H$$

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Radial Excitations & Chiral Symmetry

Höll, Krassnigg, Roberts
nu-th/0406030

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- $\Rightarrow f_H = 0$

  ALL pseudoscalar mesons except $\pi(140)$ in chiral limit

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Höll, Krassnigg, Roberts
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  ALL pseudoscalar mesons except $\pi(140)$ in chiral limit
- Dynamical Chiral Symmetry Breaking

  – Goldstone's Theorem –

  impacts upon *every* pseudoscalar meson

McNeile and Michael
he-la/0607032

Radial Excitations & Lattice-QCD

- *When we first heard about [this result] our first reaction was a combination of “that is remarkable” and “unbelievable”.*

Radial Excitations & Lattice-QCD

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  $\Rightarrow f_{\pi_1} < 8.4$ MeV
  Diehl & Hiller
  he-ph/0105194

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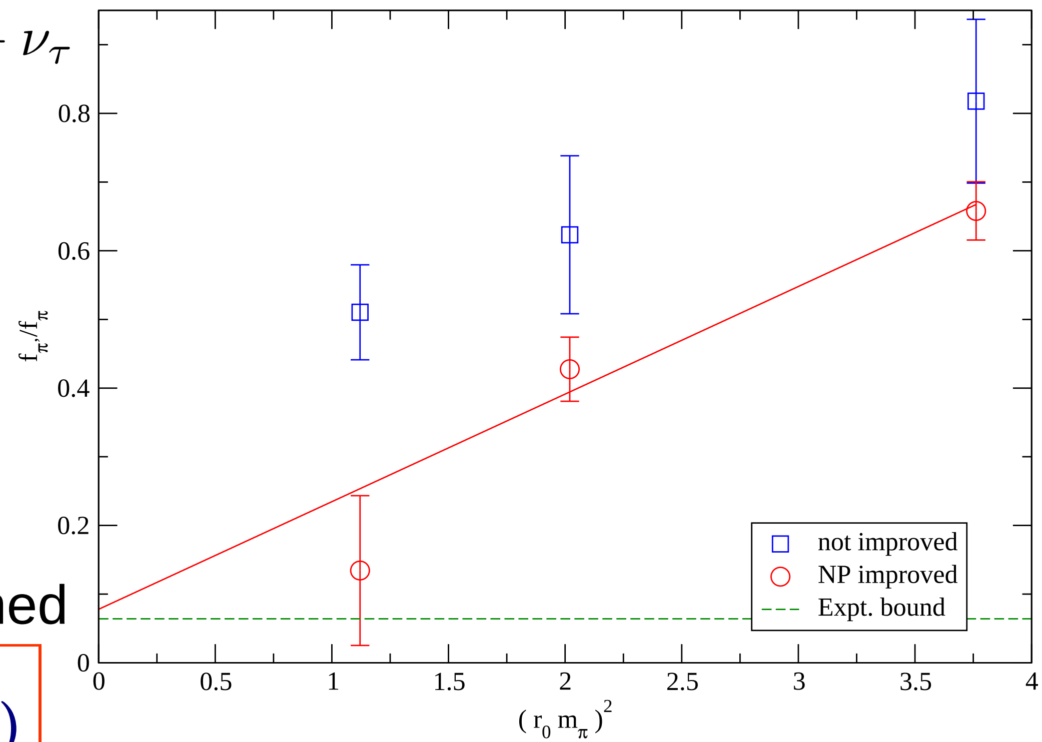
  Diehl & Hiller
  he-ph/0105194
- Lattice-QCD check:
  $16^3 \times 32$,
  $a \sim 0.1$ fm,
  two-flavour, unquenched

$$\boxed{\Rightarrow \frac{f_{\pi_1}}{f_\pi} = \mathbf{0.078\,(93)}}$$



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he-la/0607032

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- CLEO: $\tau \to \pi(1300) + \nu_\tau$
  $\Rightarrow f_{\pi_1} < 8.4\,$MeV
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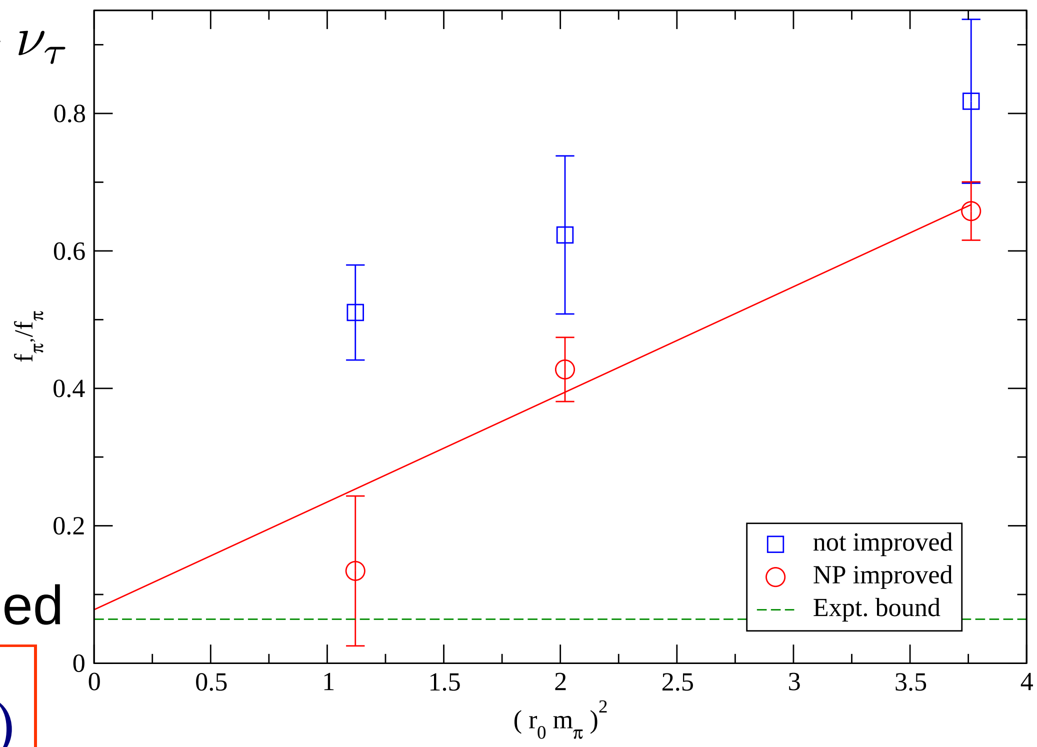

- Lattice-QCD check:
  $16^3 \times 32$,
  $a \sim 0.1\,$fm,
  two-flavour, unquenched

$$\boxed{\Rightarrow \frac{f_{\pi_1}}{f_\pi} = 0.078\,(93)}$$

- Full ALPHA formulation is required to see suppression, because PCAC relation is at the heart of the conditions imposed for improvement (determining coefficients of irrelevant operators)

Radial Excitations & Lattice-QCD

McNeile and Michael
he-la/0607032

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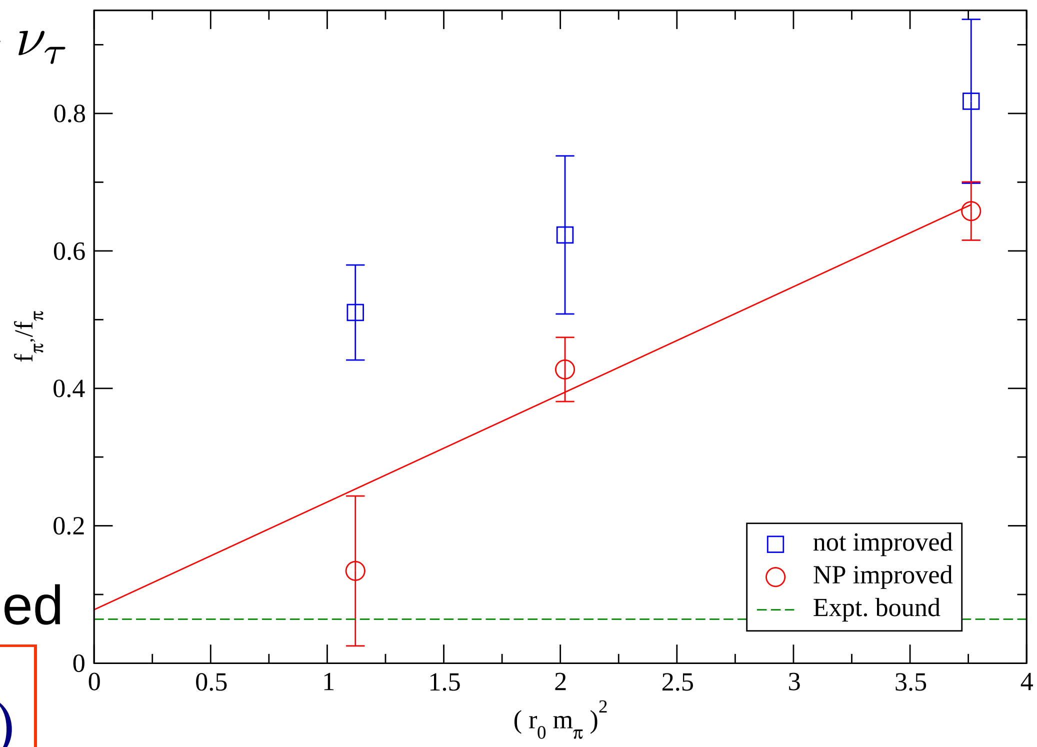
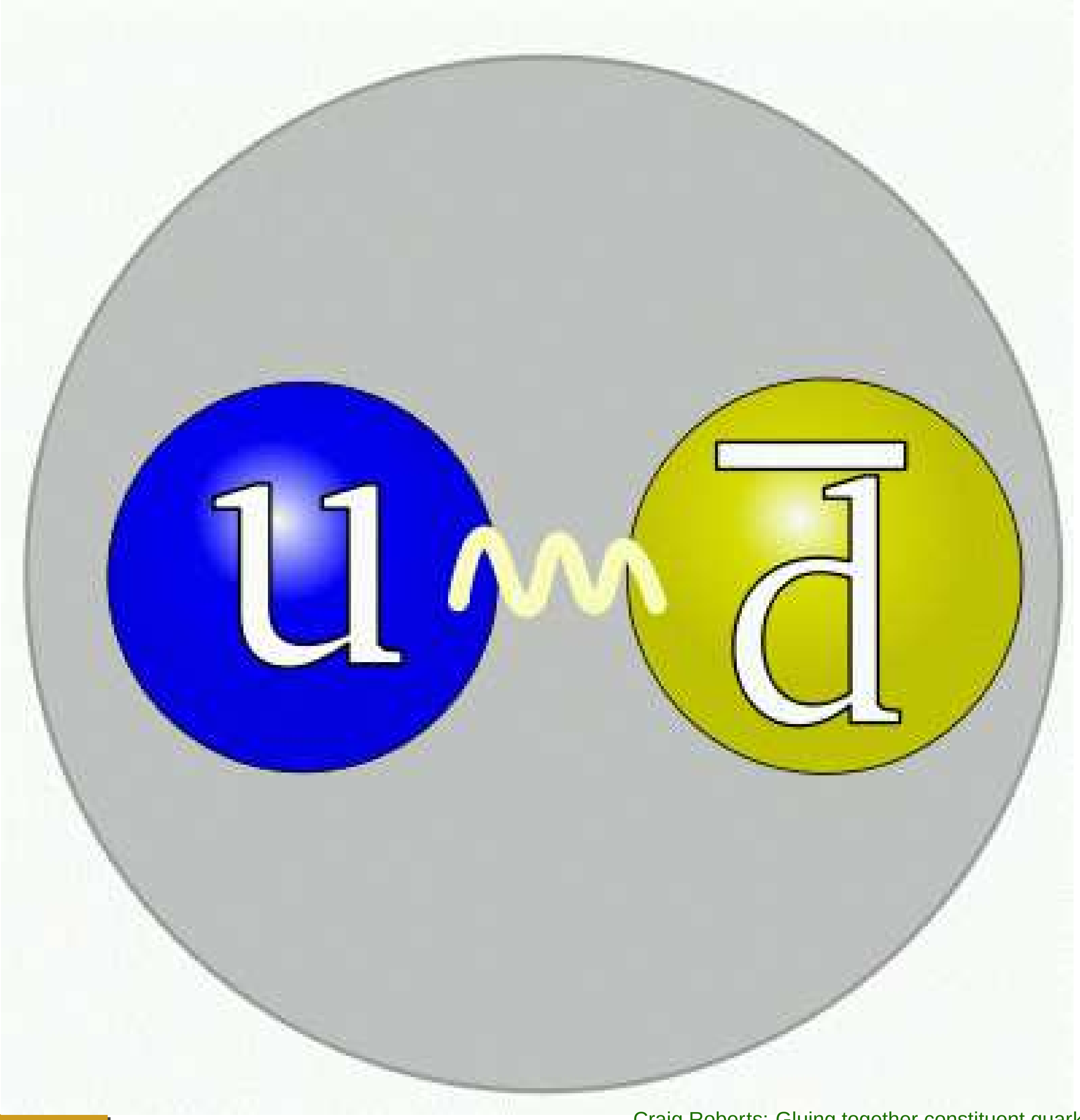


- *The suppression of f_{π_1} is a useful benchmark that can be used to tune and validate lattice QCD techniques that try to determine the properties of excited states mesons.*

Answer for the pion



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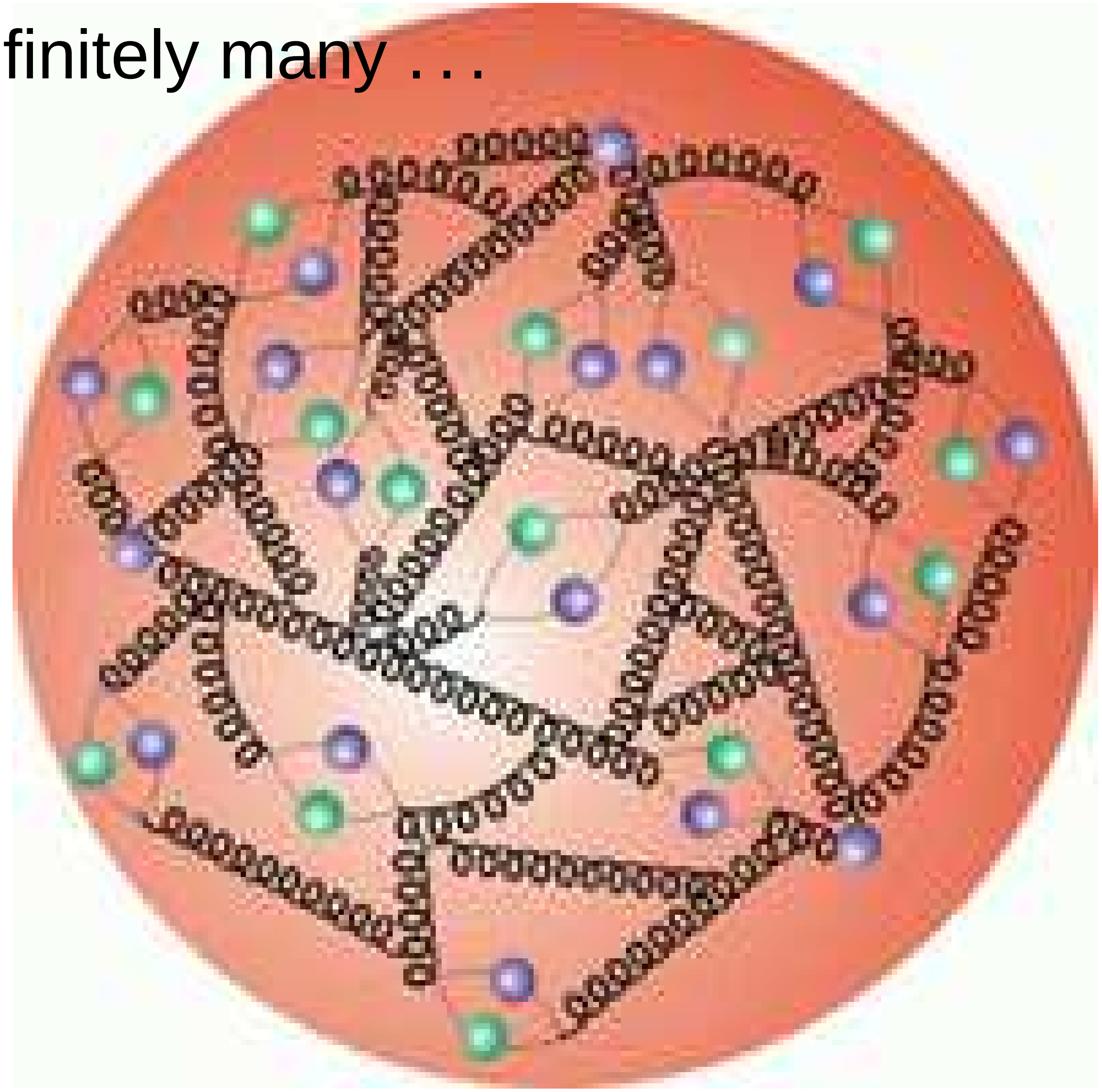
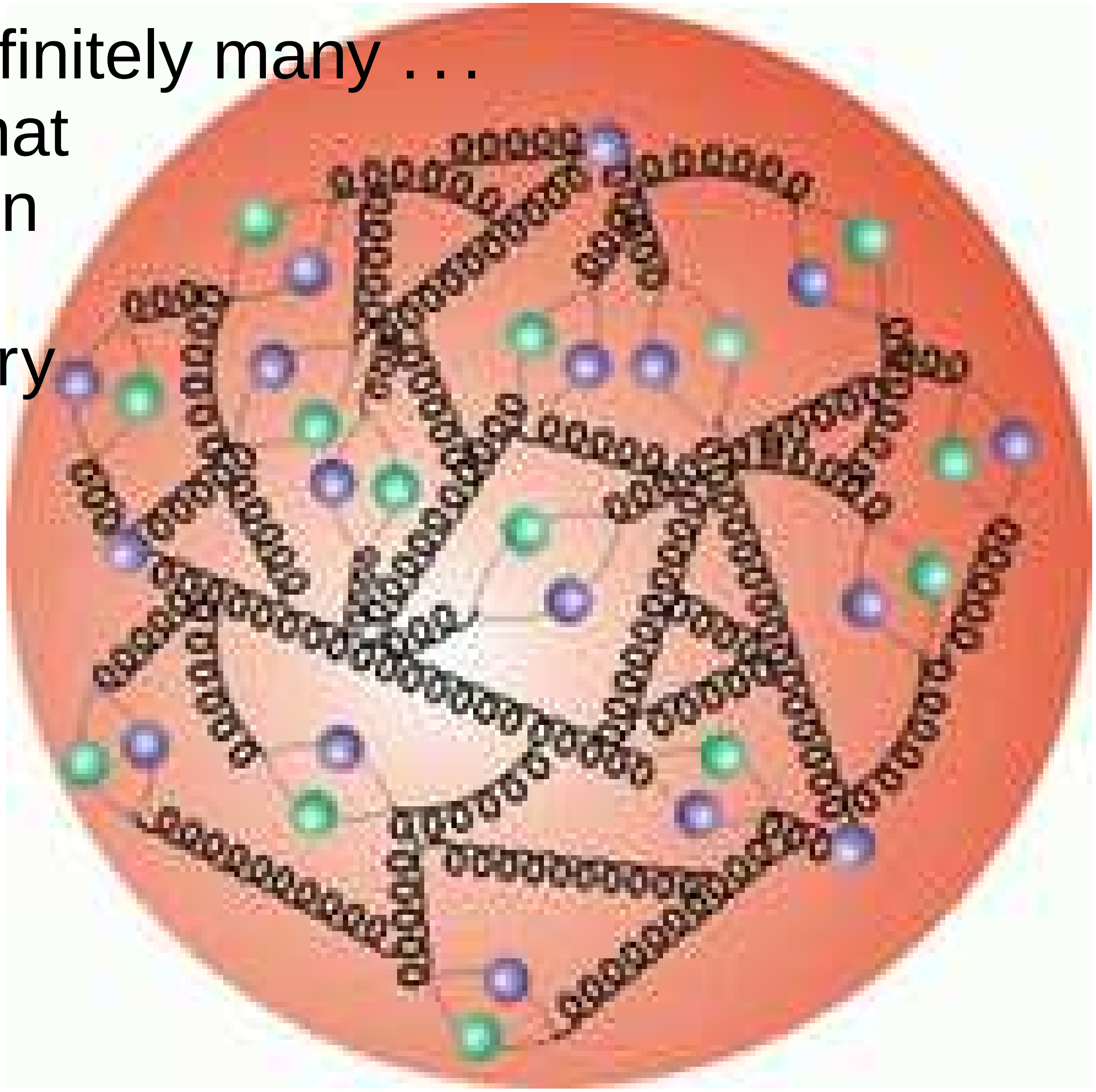
Answer for the pion

Two → Infinitely many . . .



Answer for the pion

Two → Infinitely many . . .
Handle that properly in quantum field theory



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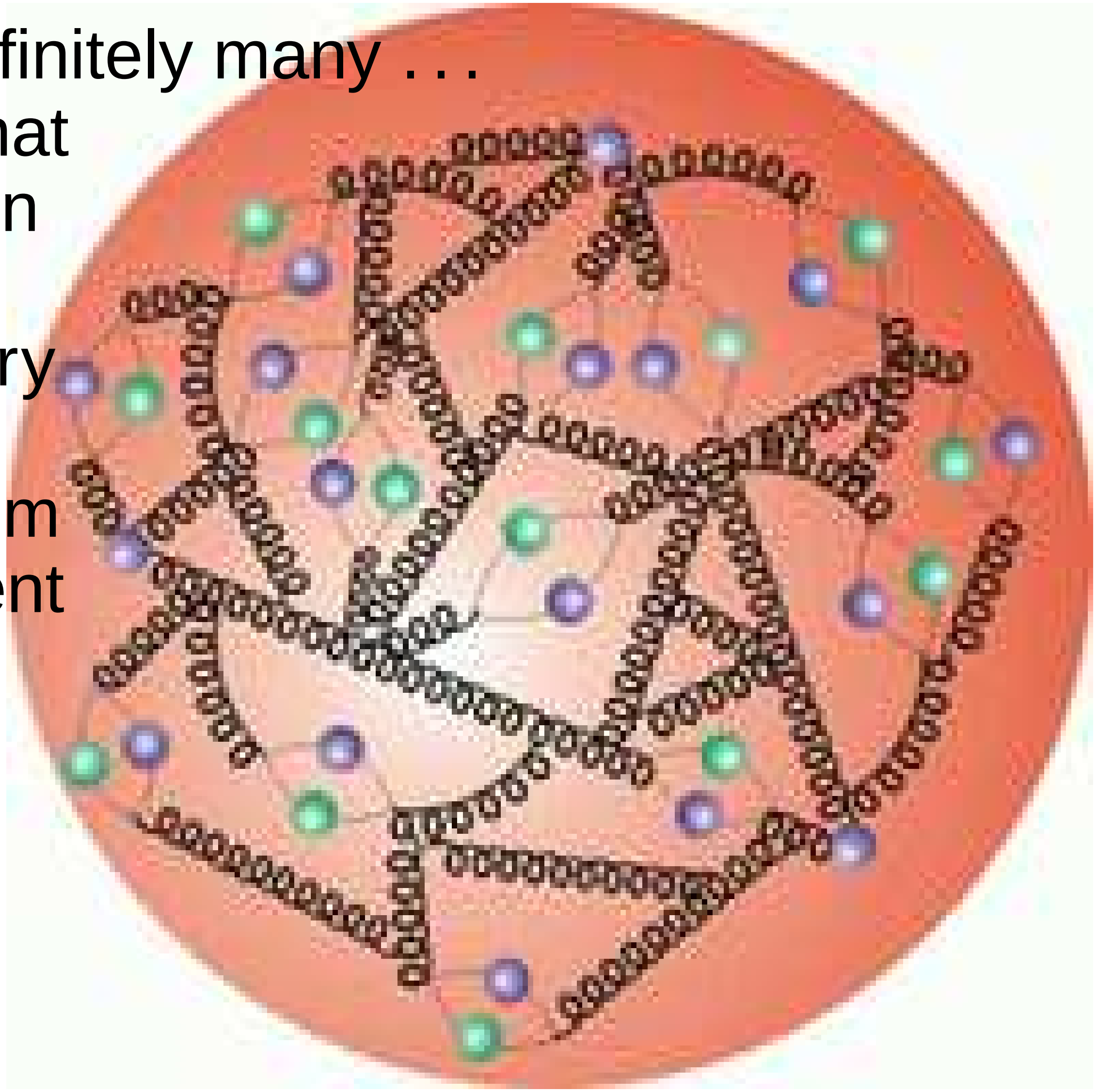

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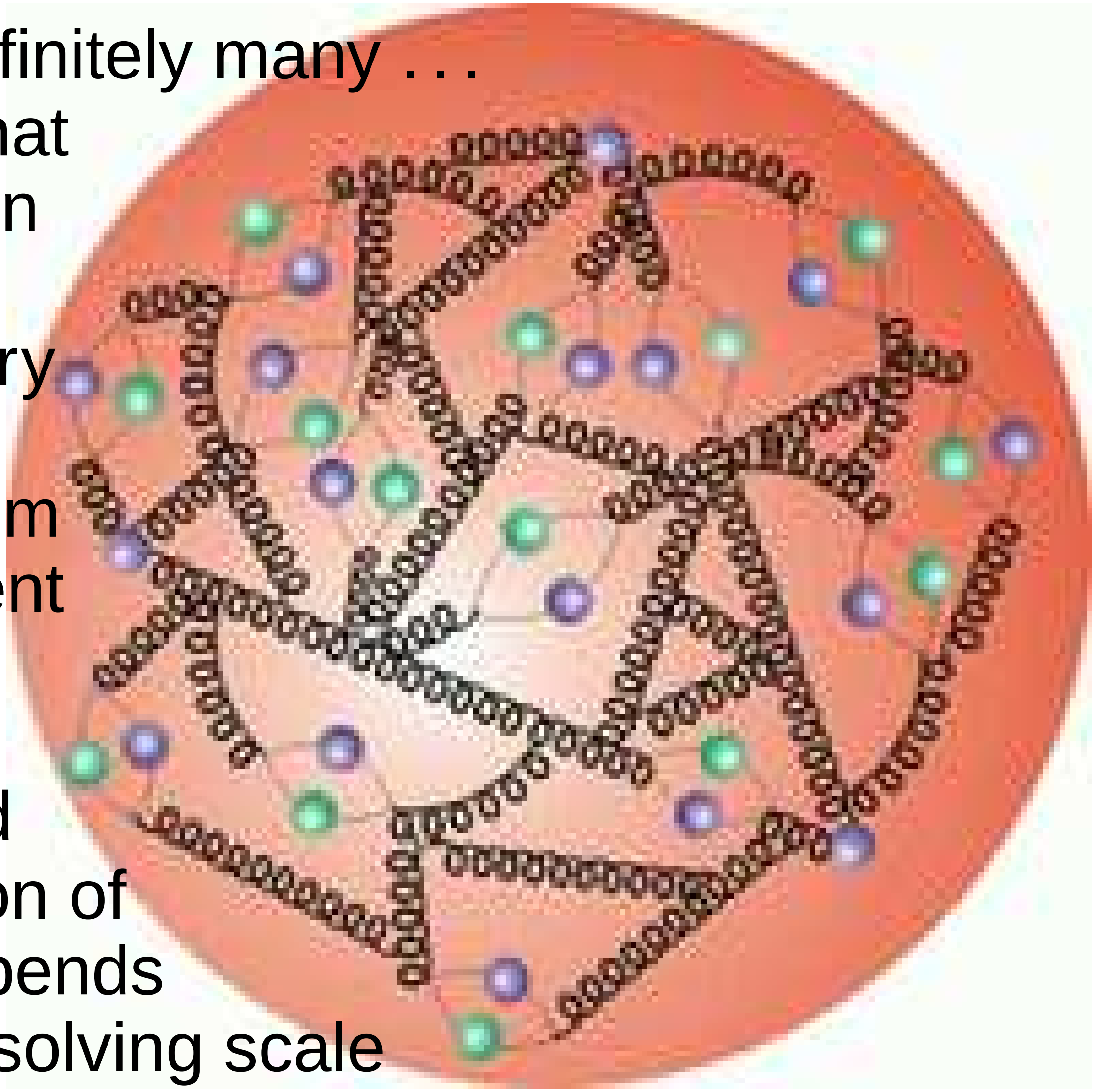
Answer for the pion

Two $\rightarrow$ Infinitely many . . .
Handle that properly in quantum field theory
. . .
momentum-dependent dressing
. . .
perceived distribution of mass depends on the resolving scale



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Thomas Jefferson National Accelerator Facility

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- World's Premier Hadron Physics Facility

JLab

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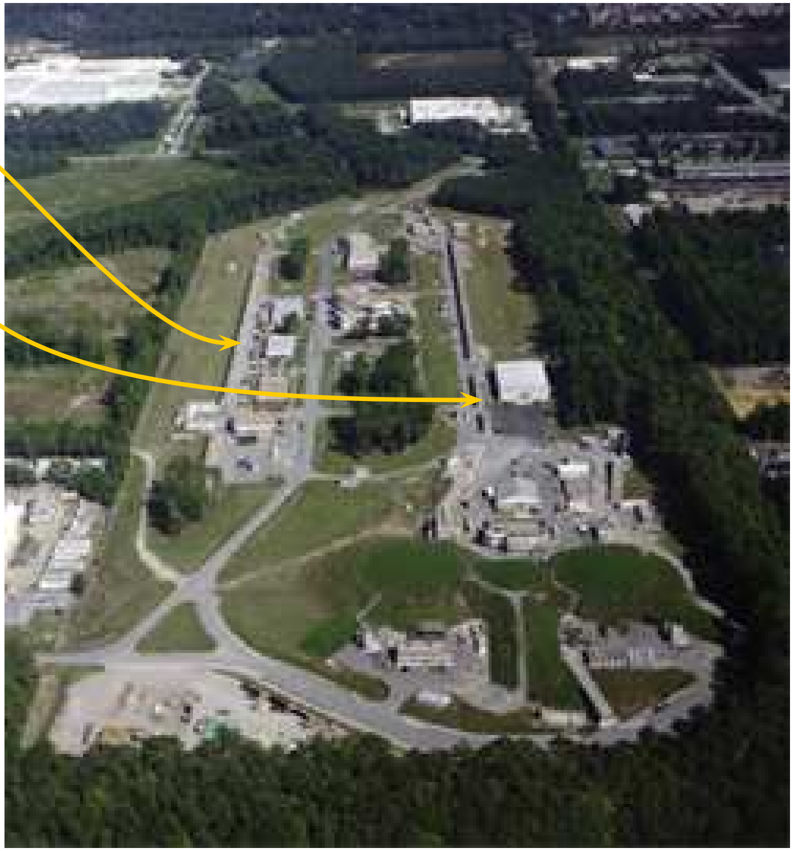

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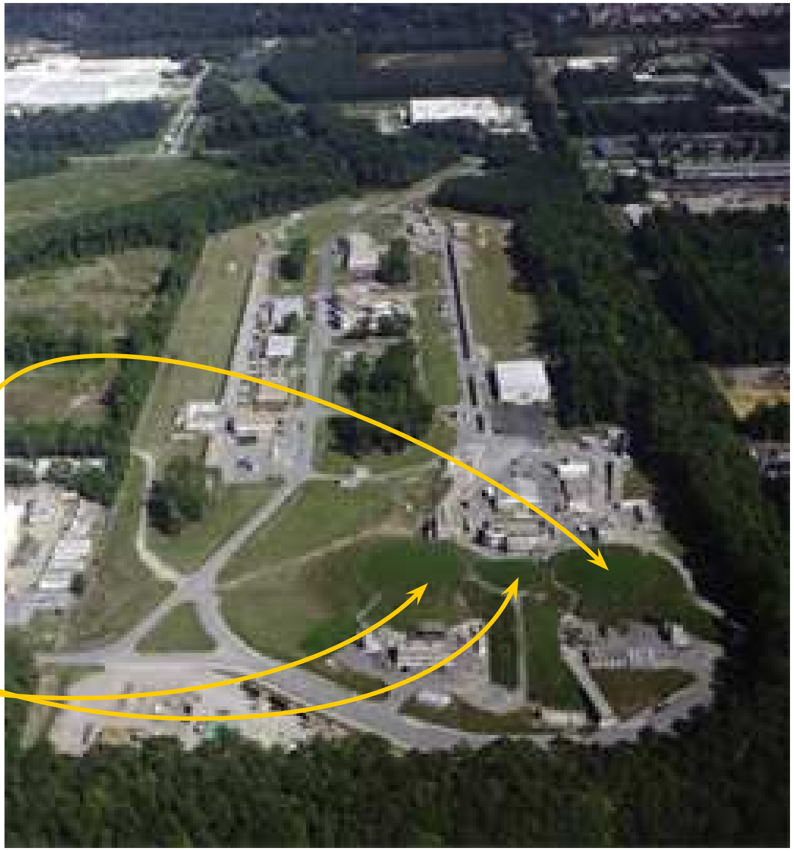
- Once desired energy is reached, Beam is directed into Experimental Halls A, B and C



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- Electrons accelerated by repeated journeys along *linacs*
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- Current Peak Electron Beam Energy Nearly 6 GeV

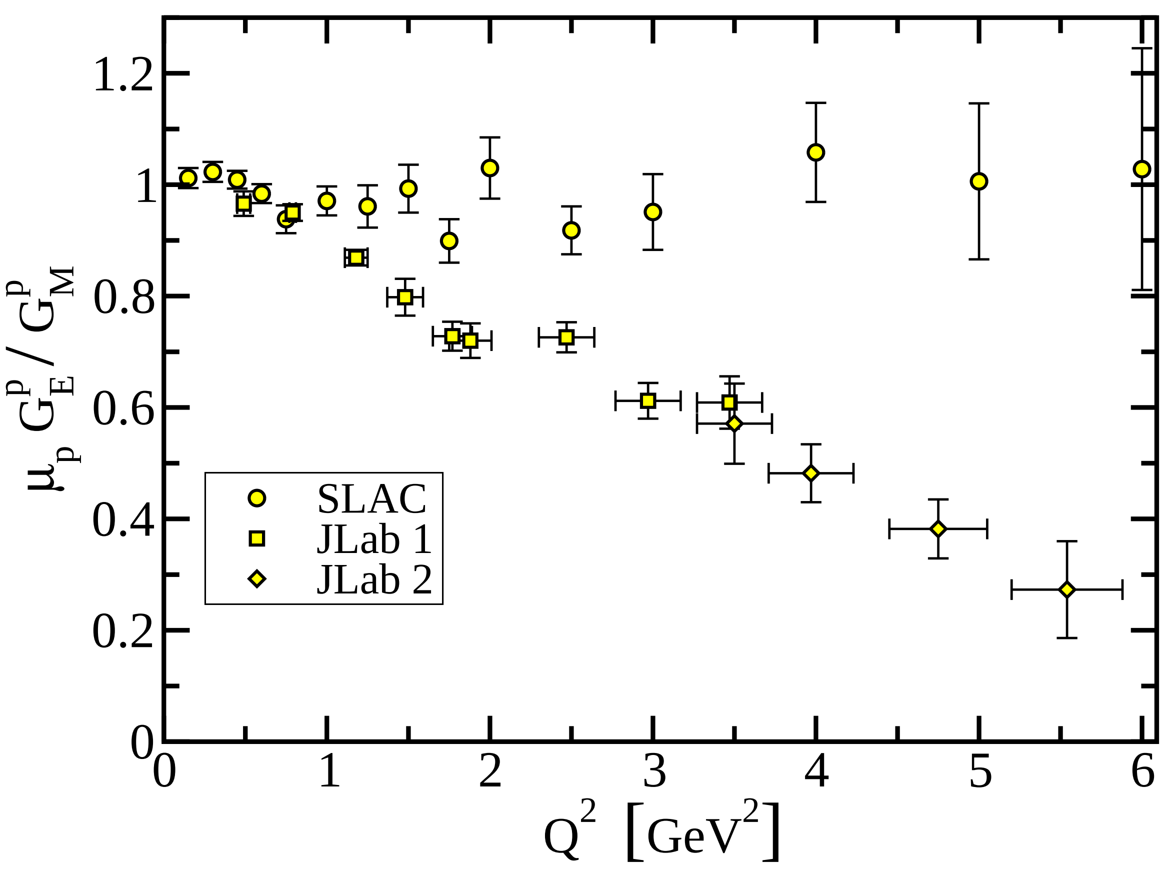
JLab Hall-A

JLab Hall-A

- Measured Ratio of

  Proton's Electric and Magnetic Form Factors

JLab Hall-A



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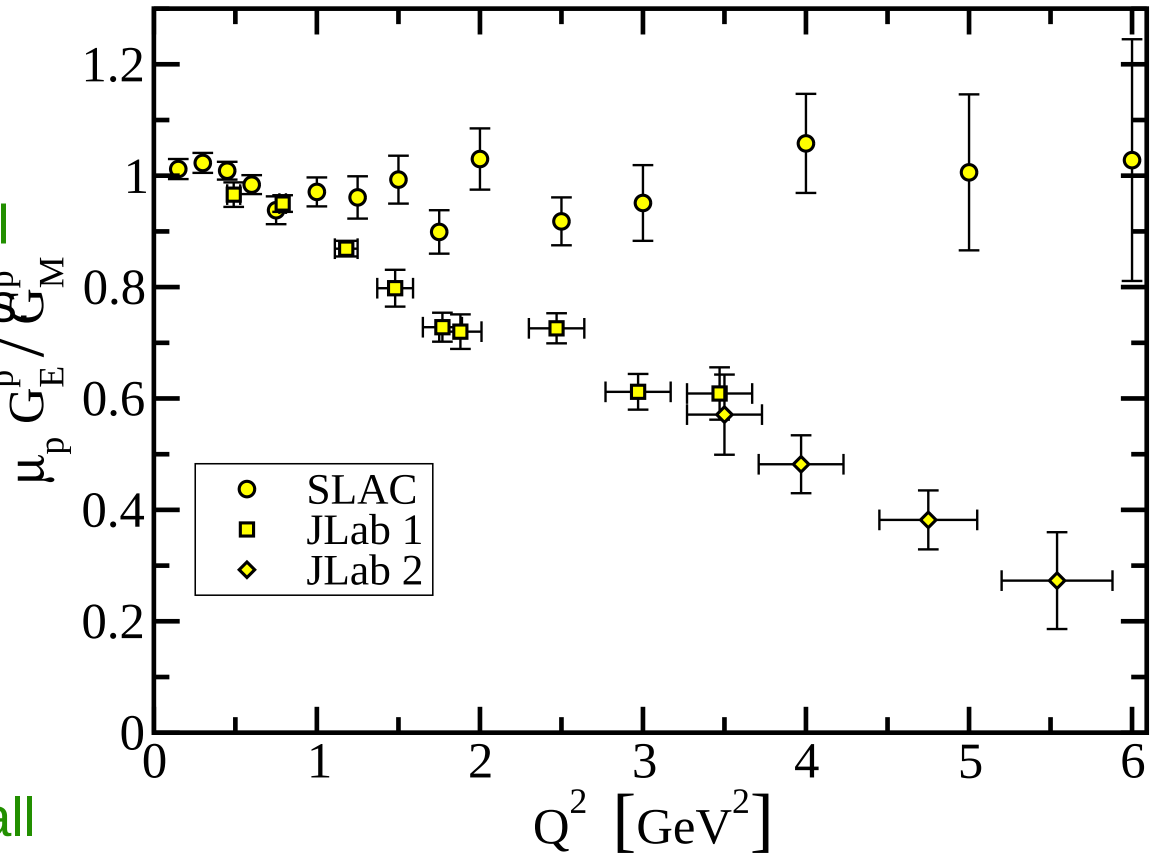
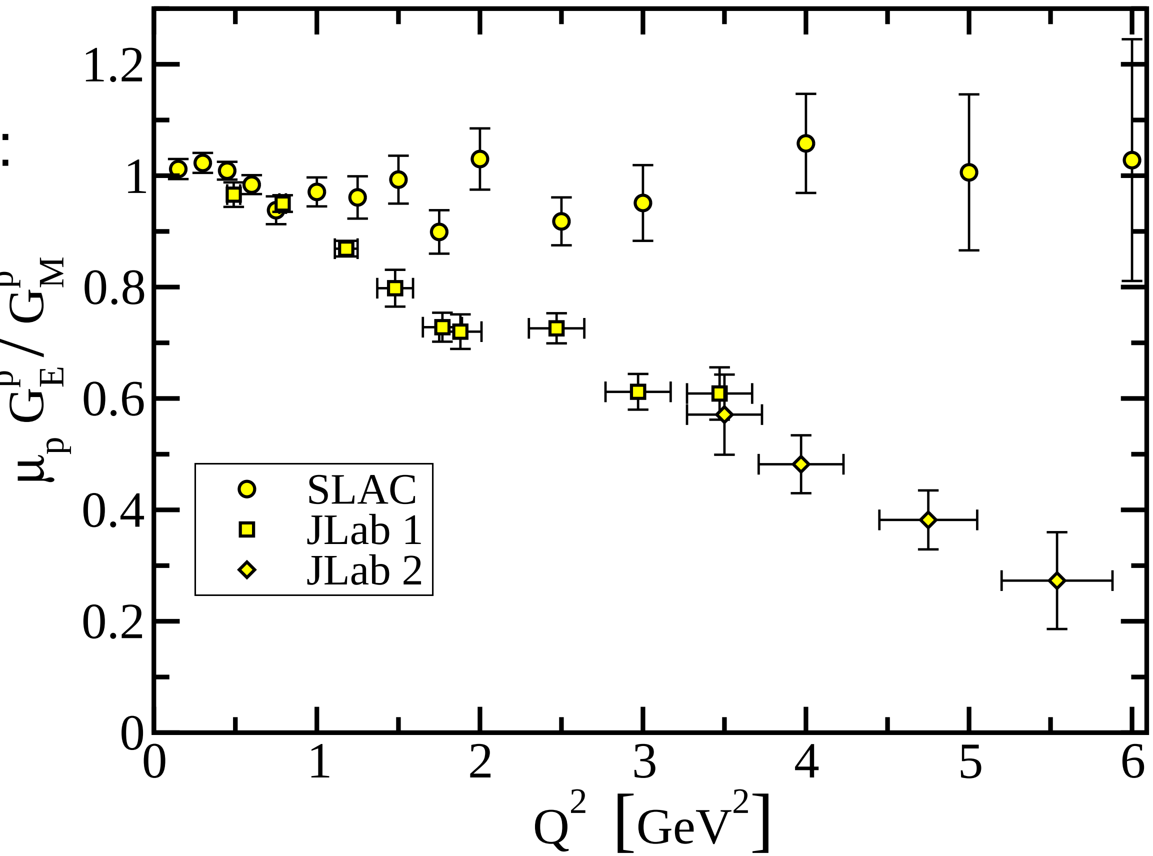
JLab Hall-A

- Walker *et al.*, Phys. Rev. **D 49**, 5671 (1994). (SLAC)
- Jones *et al.*, JLab Hall A Collaboration, Phys. Rev. Lett. **84**, 1398 (2000)
- Gayou, *et al.*, Phys. Rev. **C 64**, 038202 (2001)
- Gayou, *et al.*, JLab Hall A Collaboration, Phys. Rev. Lett. **88** 092301 (2002)



JLab Hall-A

- If JLab Correct, then
  Completely
  Unexpected Result:
  In the Proton
  – On Relativistic
  Domain
  – Distribution of
  Quark-Charge
  Not Equal
  Distribution of
  Quark-Current!



New Challenges

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- Move on to the problem of a symmetry preserving treatment of hybrids and exotics.

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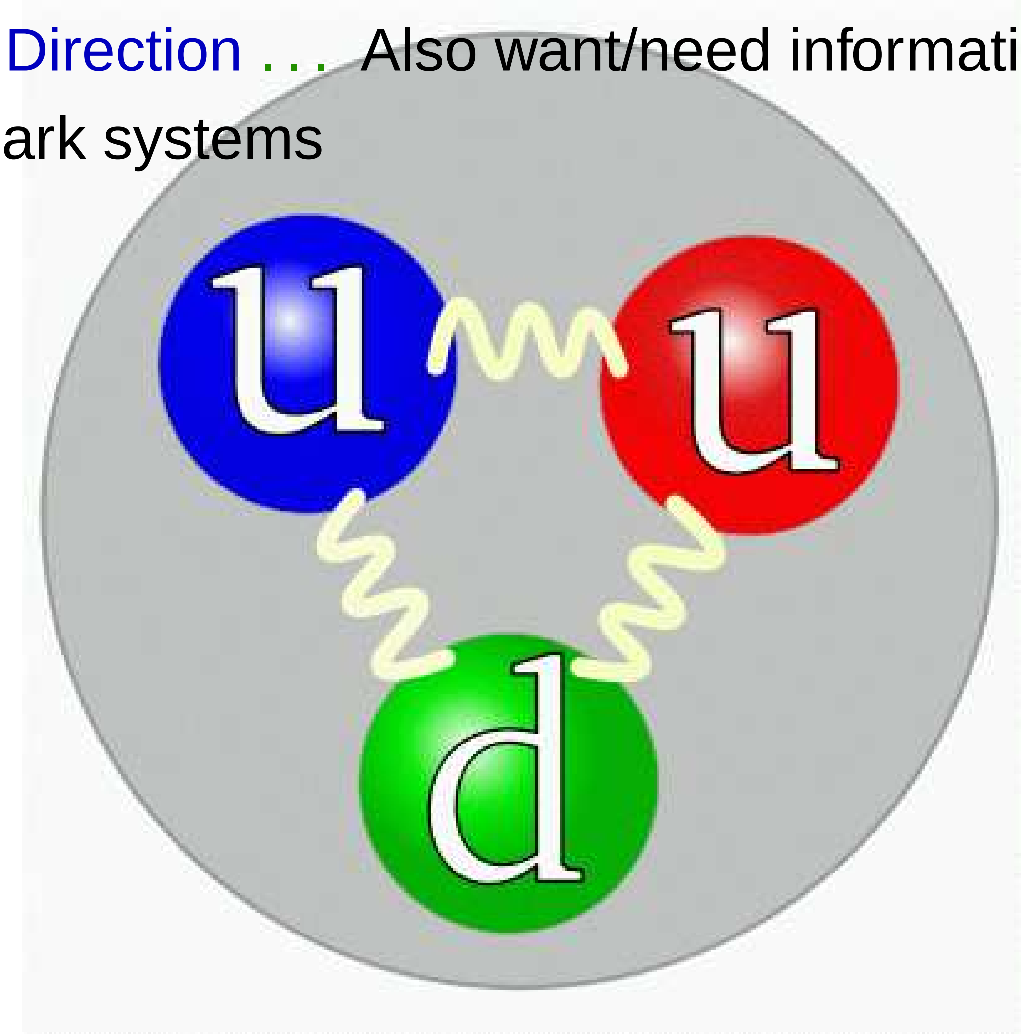
New Challenges

- Another Direction . . . Also want/need information about three-quark systems



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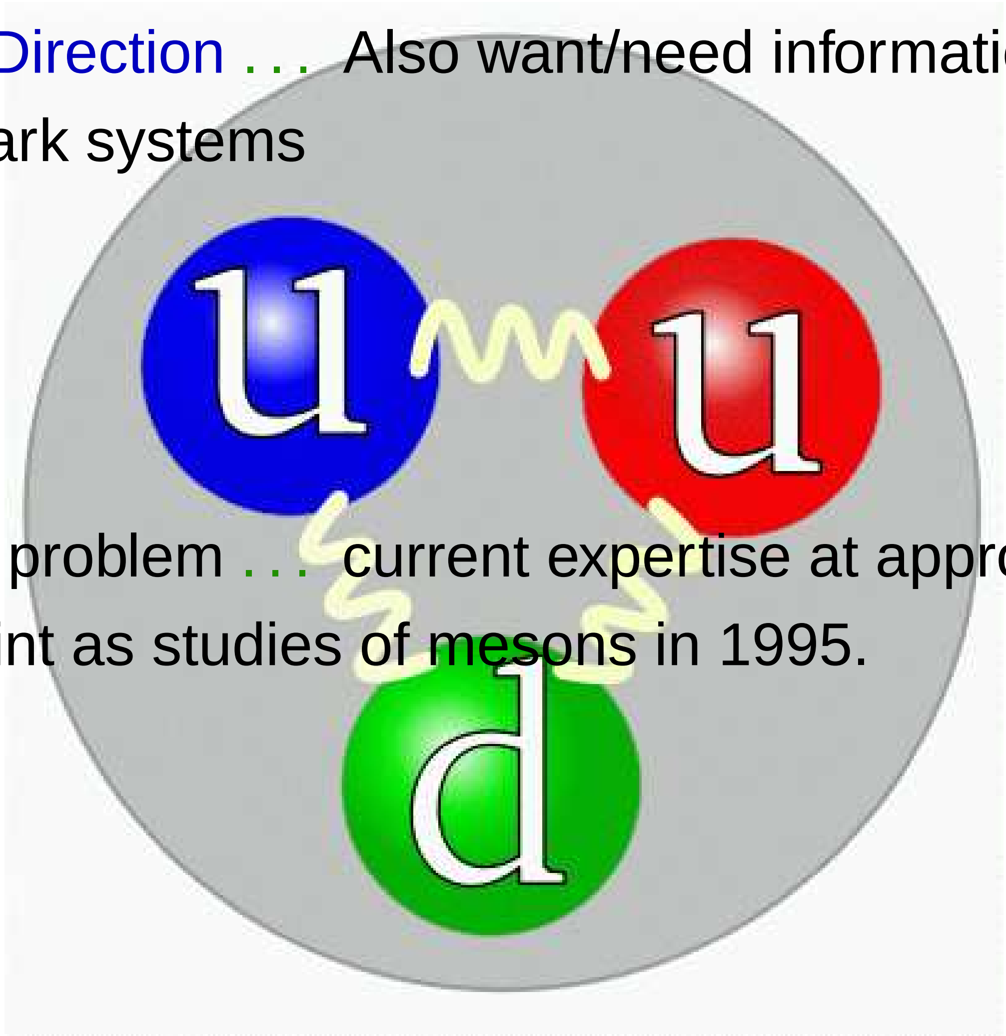

- With this problem . . . current expertise at approximately same point as studies of mesons in 1995.

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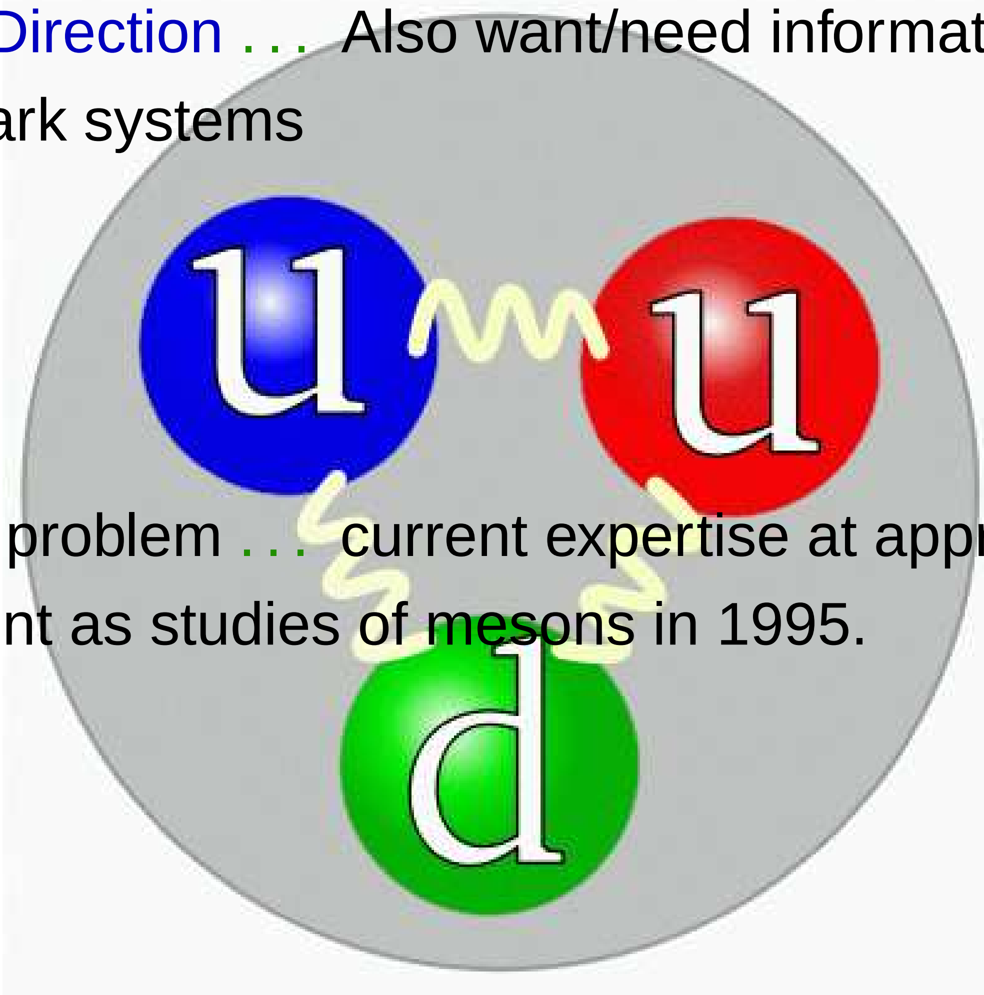
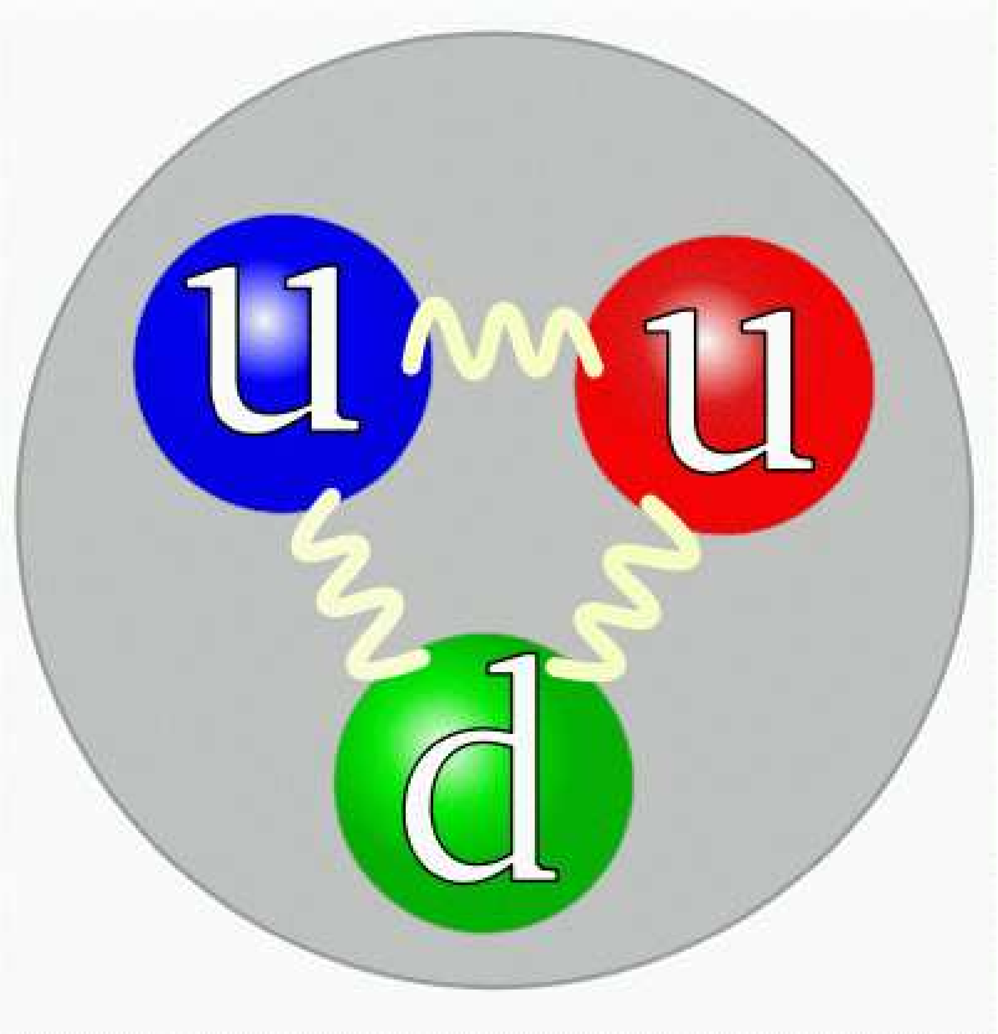


- With this problem . . . current expertise at approximately same point as studies of mesons in 1995.

- Namely . . . Model-building and Phenomenology, constrained by the DSE results outlined already.

Nucleon . . .
Three-body Problem?



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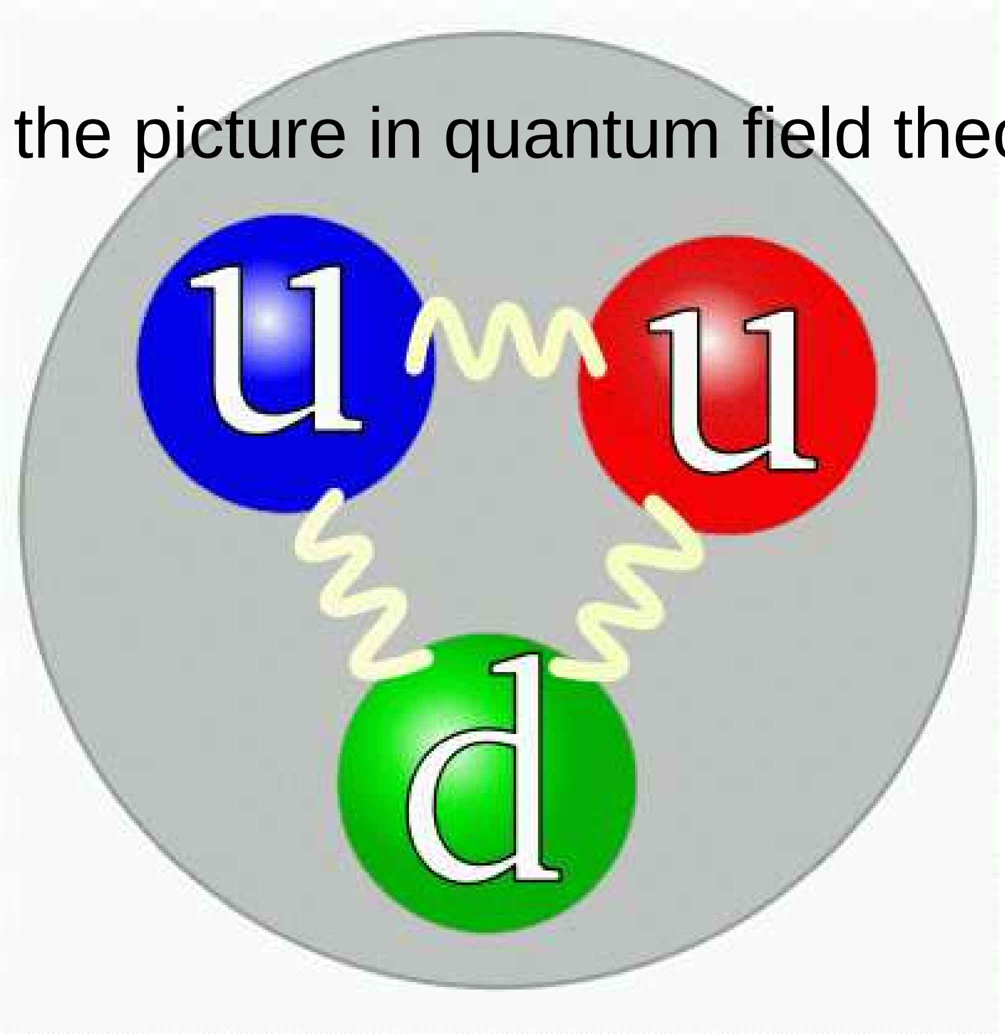
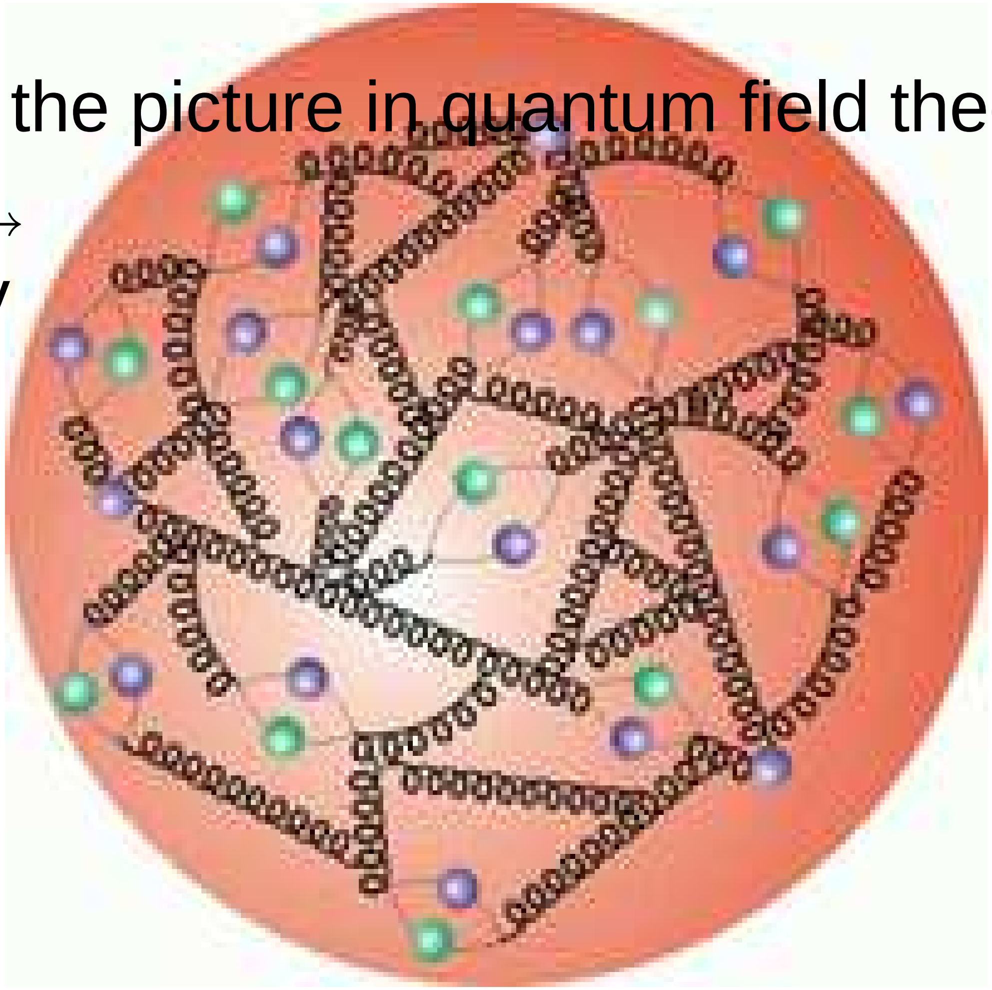
- What is the picture in quantum field theory?



Nucleon . . .
Three-body Problem?

- What is the picture in quantum field theory?
- Three $\rightarrow$ infinitely many!



Faddeev equation

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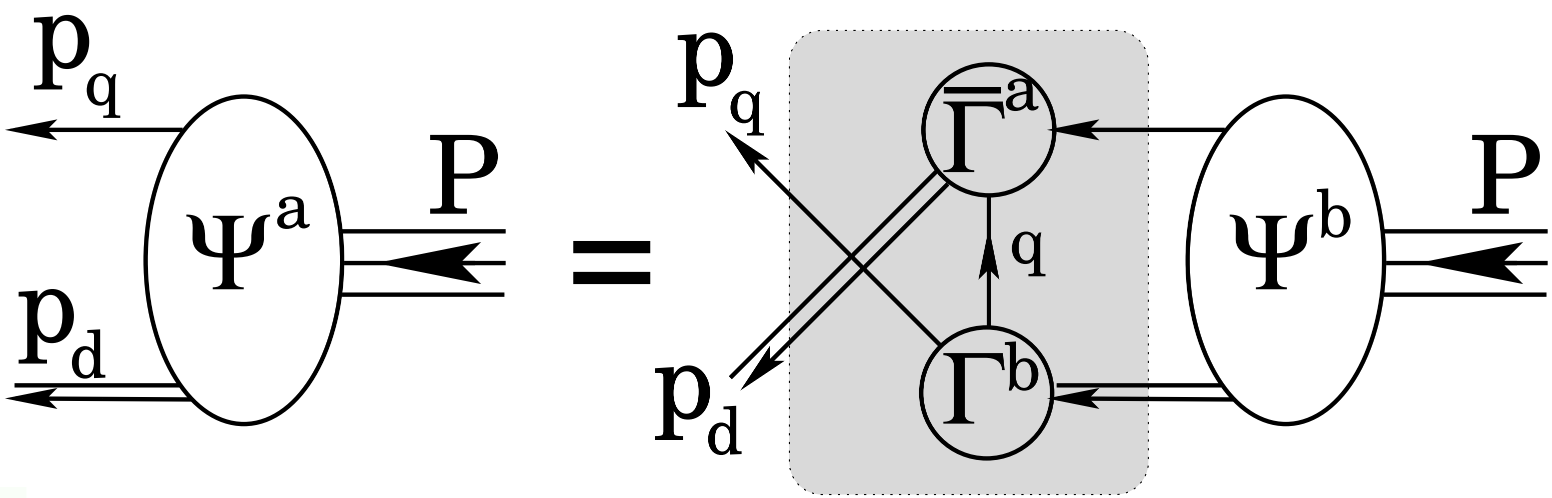

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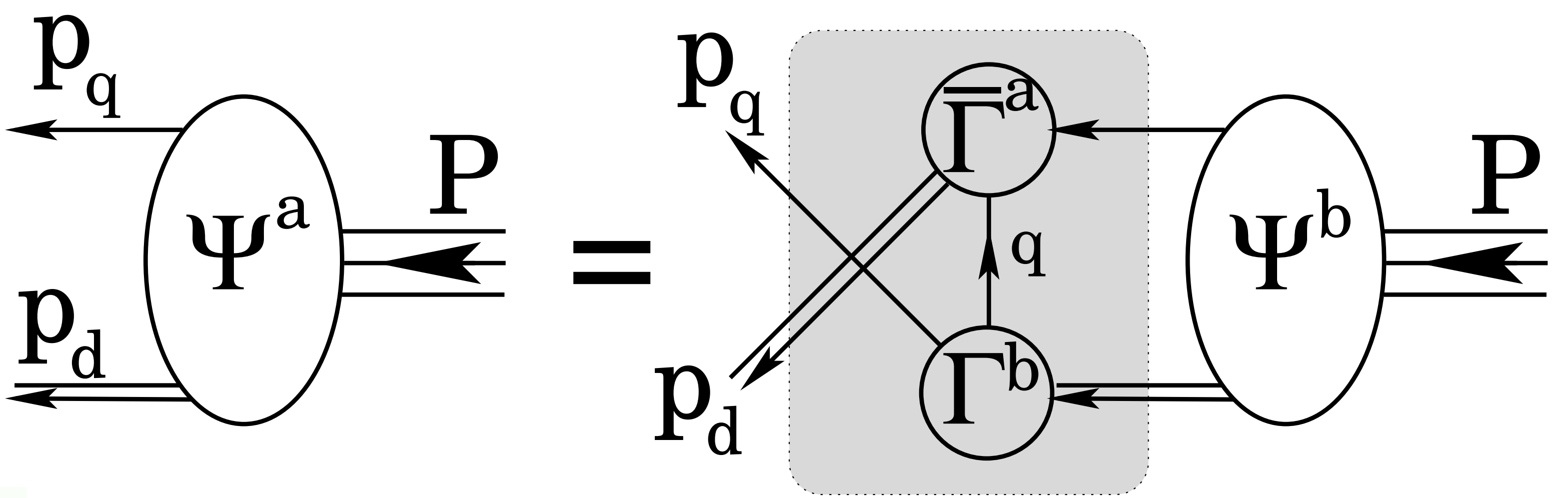
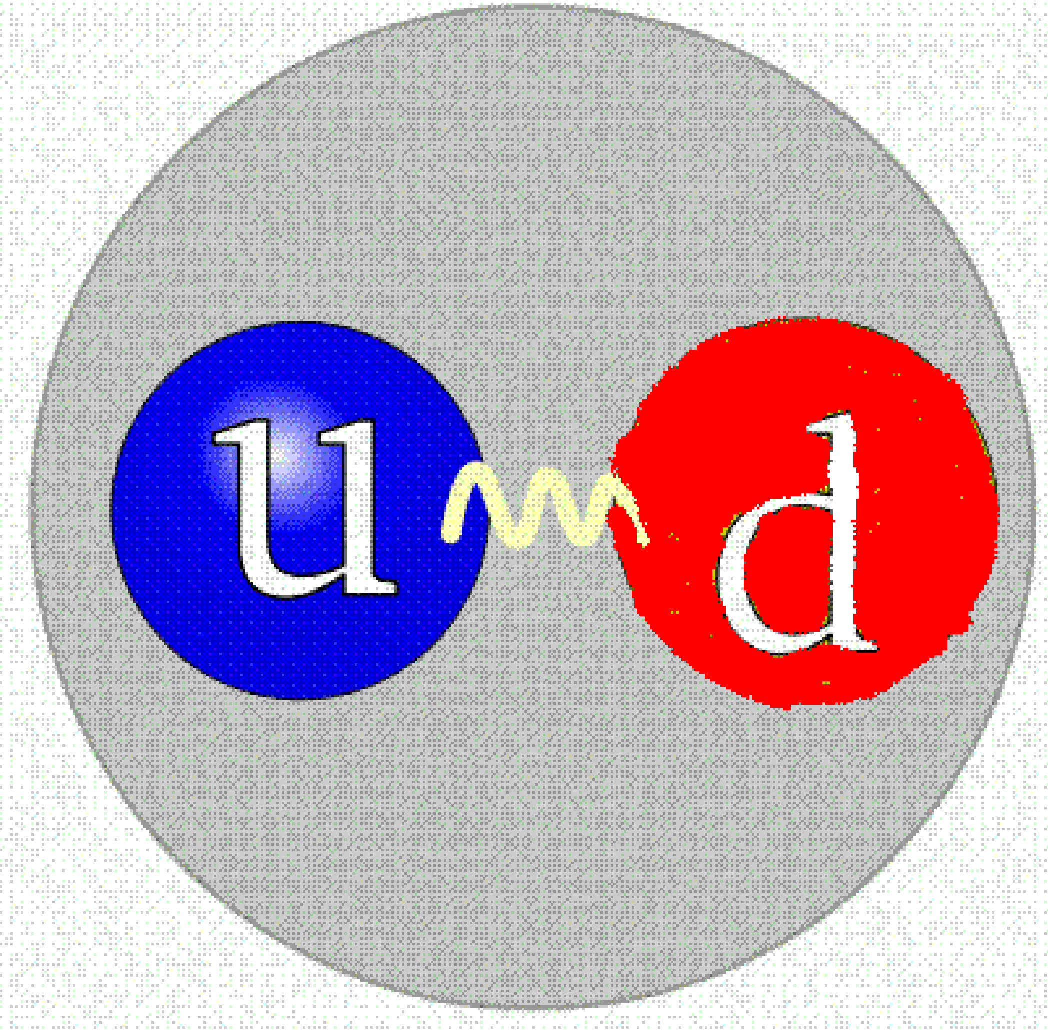


- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

Diquark correlations



QUARK-QUARK

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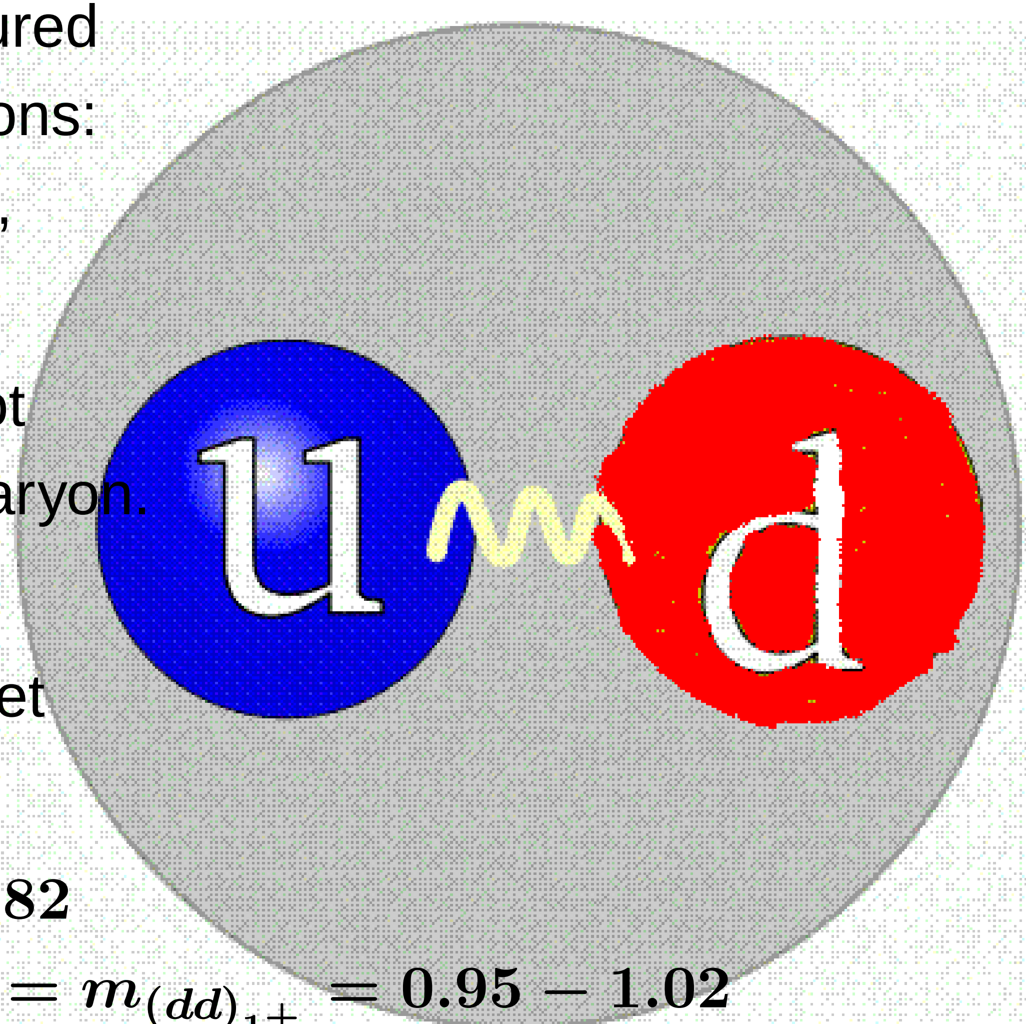
Diquark correlations

- Same interaction that describes mesons also generates three coloured quark-quark correlations: blue–red, blue–green, green–red
- Confined … Does not escape from within baryon.
- Scalar is isosinglet, Axial-vector is isotriplet
- DSE and lattice-QCD

$$m_{[ud]_{0^+}} = 0.74 - 0.82$$

$$m_{(uu)_{1^+}} = m_{(ud)_{1^+}} = m_{(dd)_{1^+}} = 0.95 - 1.02$$



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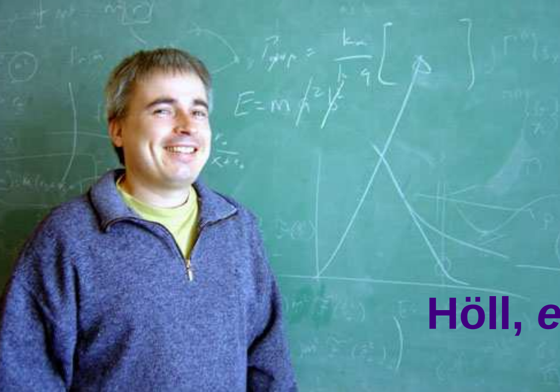
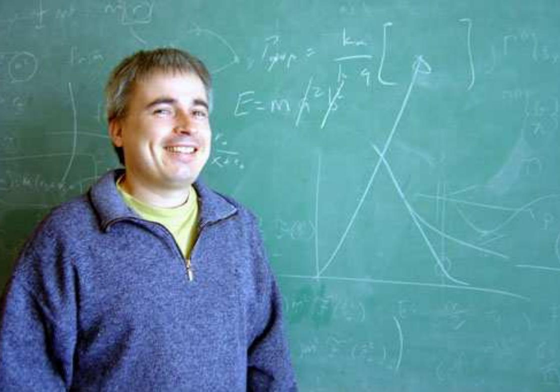


Nucleon EM Form Factors: A Précis

Höll, *et al.*: nu-th/0412046 & nu-th/0501033



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  Easily obtained:

$$\left(\frac{1}{N_H} \sum_H \frac{[M_H^{\rm exp} - M_H^{\rm calc}]^2}{[M_H^{\rm exp}]^2} \right)^{1/2} = 2\%$$

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(Oettel, Hellstern, Alkofer, Reinhardt: nucl-th/9805054)

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- Critical to anticipate pion cloud effects
  Roberts, Tandy, Thomas, *et al.*, nu-th/02010084

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Pions and Form Factors

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- Dynamical coupled-channels model ... Analyzed extensive JLab data ... Completed a study of the $\Delta(1236)$
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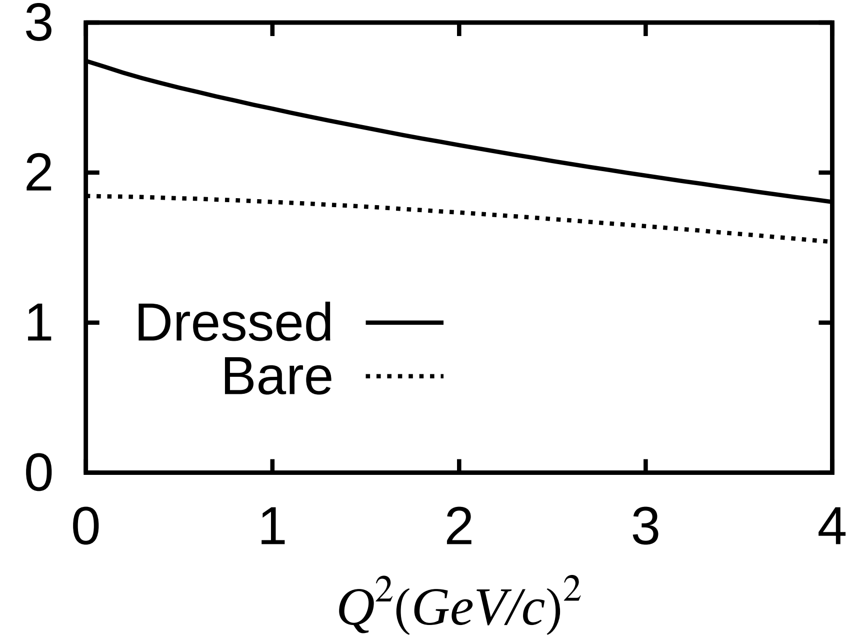
Ratio of the M1 form factor in $\gamma N \to \Delta$ transition and proton dipole form factor G_D. Solid curve is $G_M^*(Q^2)/G_D(Q^2)$ including pions; Dotted curve is $G_M(Q^2)/G_D(Q^2)$ without pions.



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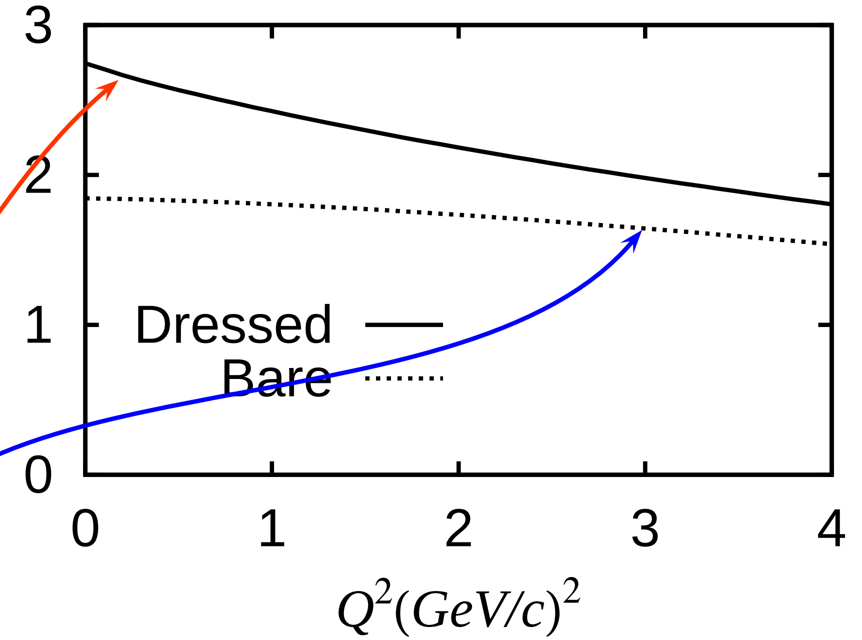

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Quark Core

- Responsible for only 2/3 of result at small Q^2
- Dominant for $Q^2 > 2 - 3\,\text{GeV}^2$

Results: Nucleon and Δ Masses

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Mass-scale parameters (in GeV) for the scalar and axial-vector diquark correlations, fixed by fitting nucleon and Δ masses

Set A – fit to the actual masses was required; whereas for

Set B – fitted mass was offset to allow for "π-cloud" contributions

set	M_N	M_Δ	m_{0^+}	m_{1^+}	ω_{0^+}	ω_{1^+}
A	0.94	1.23	0.63	0.84	0.44=1/(0.45 fm)	0.59=1/(0.33 fm)
B	1.18	1.33	0.80	0.89	0.56=1/(0.35 fm)	0.63=1/(0.31 fm)

- $m_{1^+} \to \infty$: $M_N^A = 1.15$ GeV; $M_N^B = 1.46$ GeV

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- Axial-vector diquark provides significant attraction

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- Constructive Interference: 1^{++}-diquark + $\partial_\mu \pi$

Nucleon-Photon Vertex

M. Oettel, M. Pichowsky
and L. von Smekal, nu-th/9909082

Nucleon-Photon Vertex

6 terms . . .

constructed systematically . . . current conserved automatically

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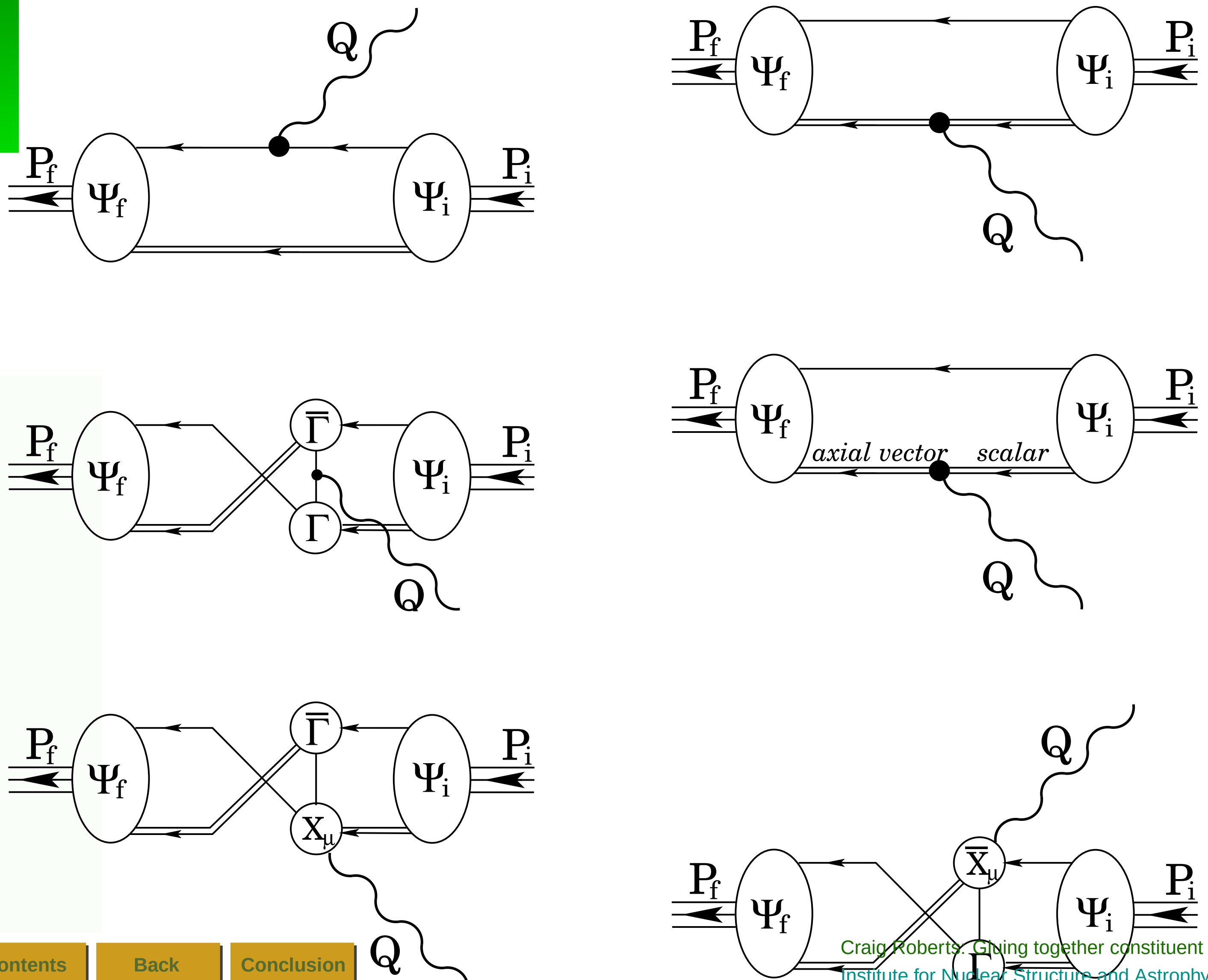

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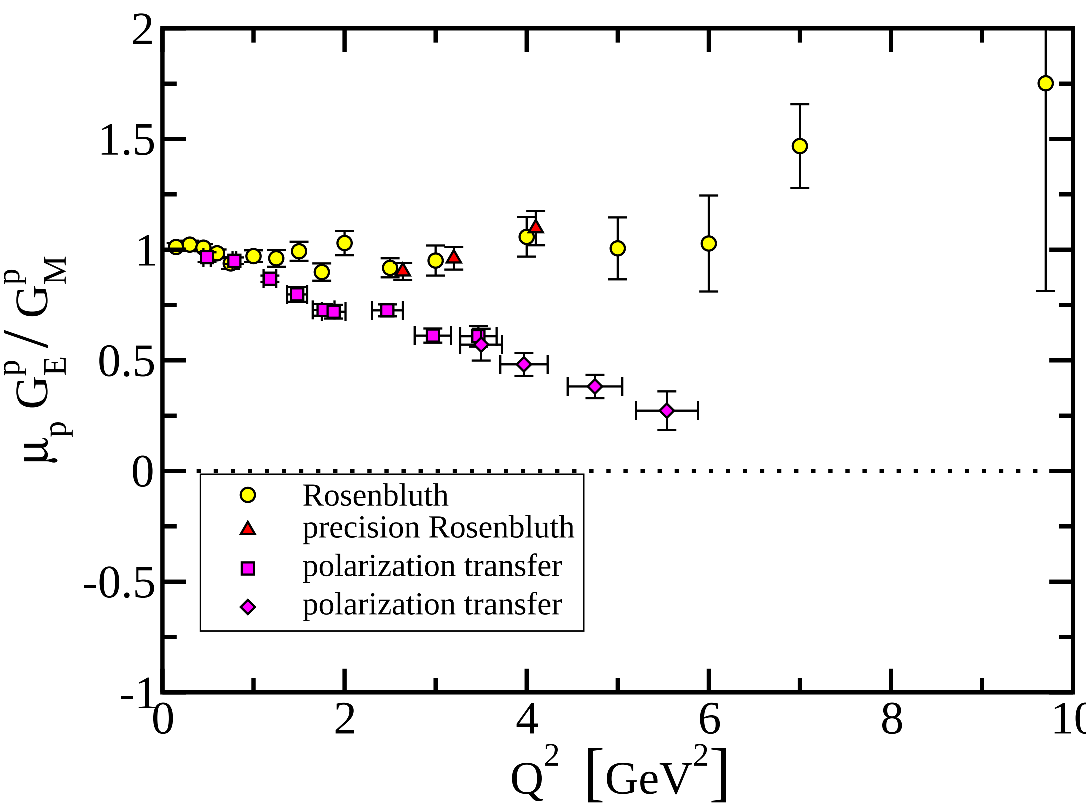
Form Factor Ratio: GE/GM



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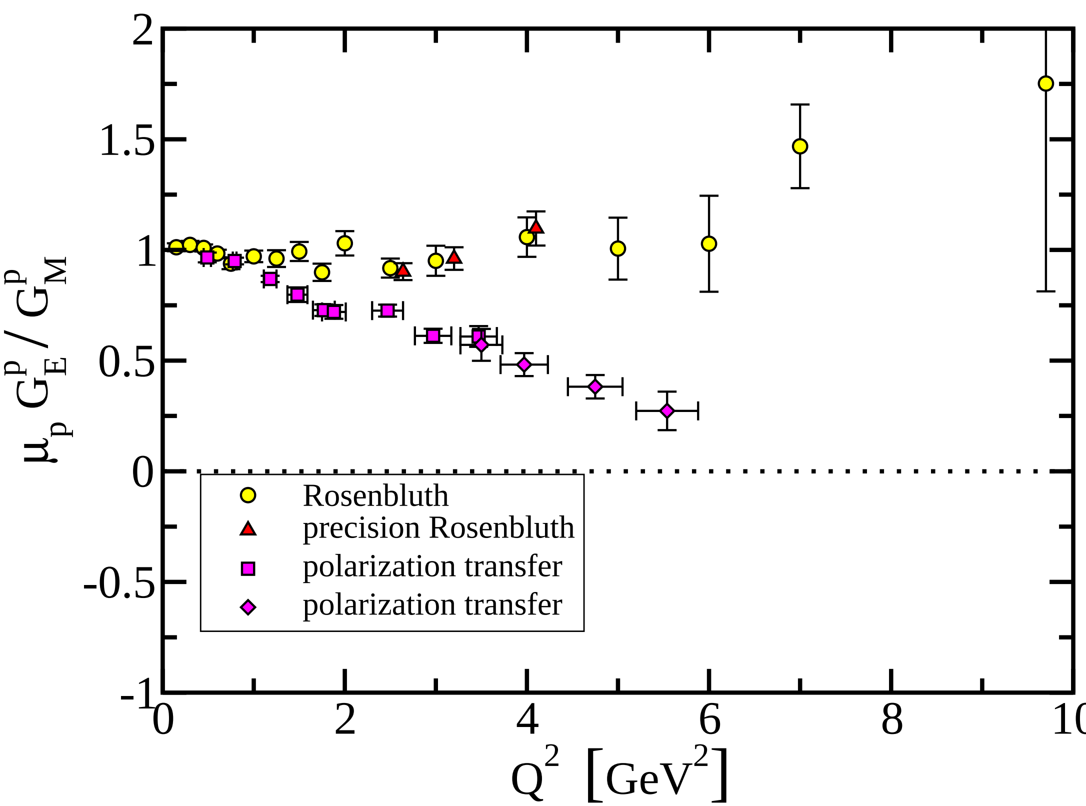

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Form Factor Ratio: GE/GM

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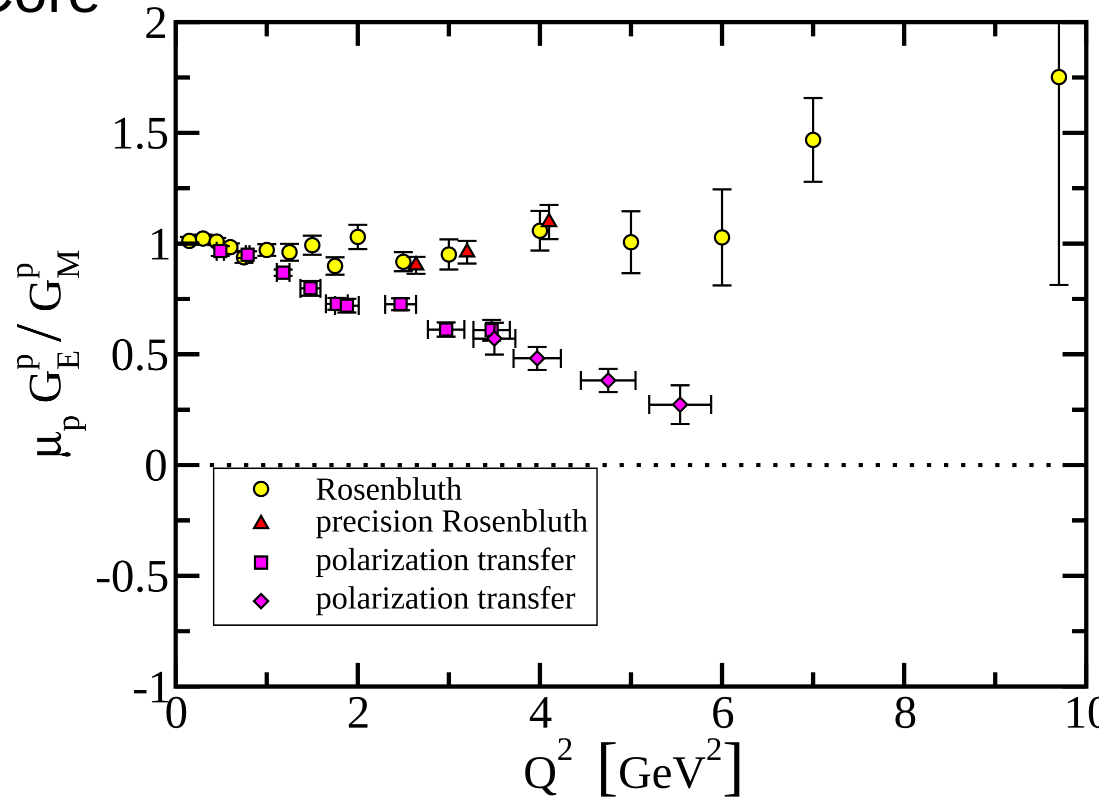

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U.S. DEPARTMENT OF ENERGY
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars
Argonne NATIONAL LABORATORY

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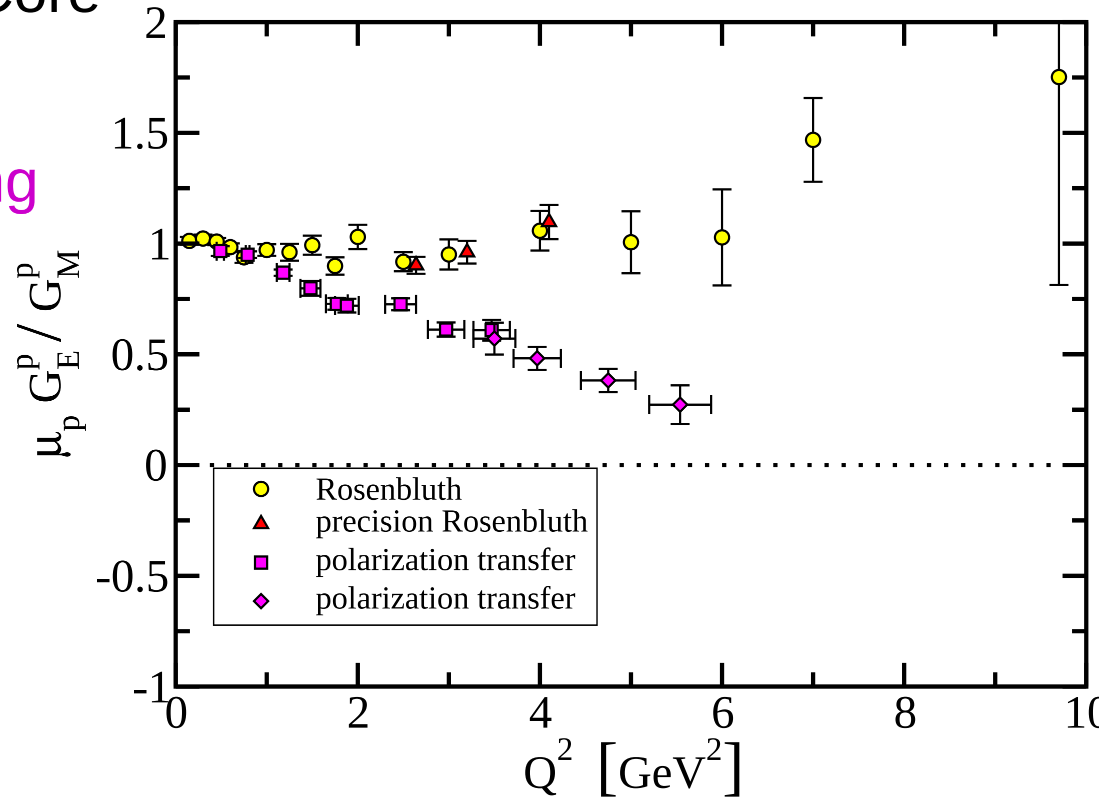

Form Factor Ratio: GE/GM

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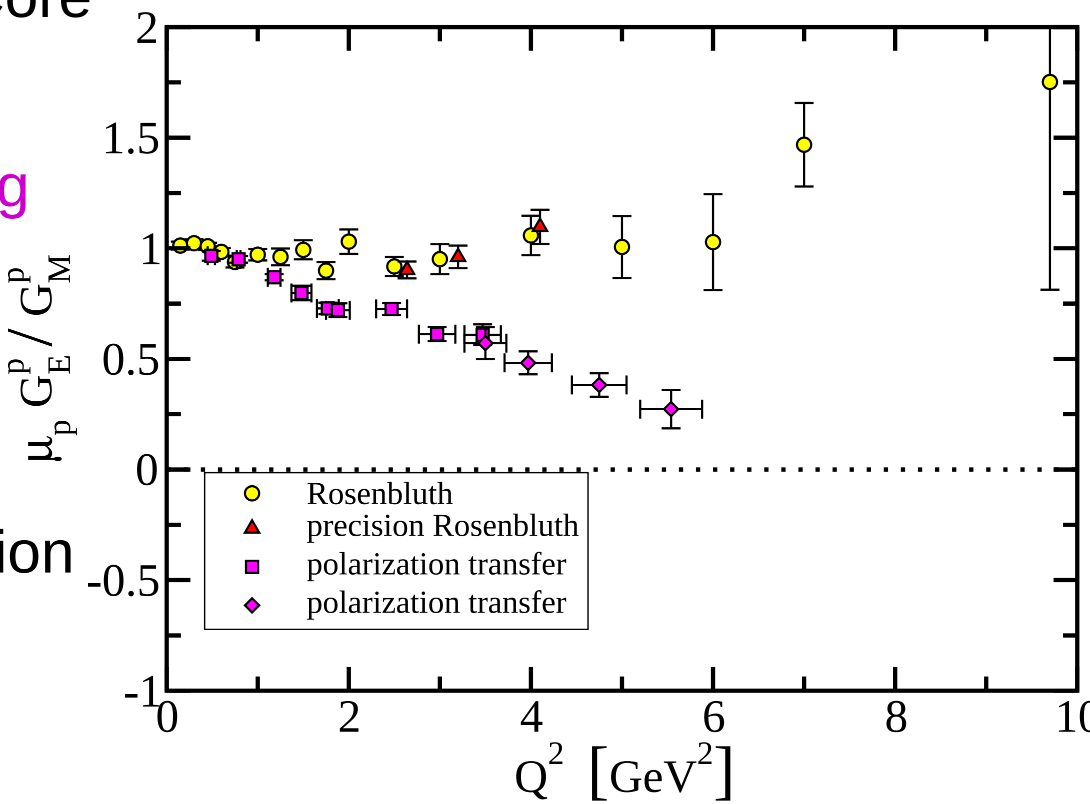
  - *Ward-Takahashi* Identity preserving current
  - Anticipate and Estimate Pion Cloud's Contribution



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Form Factor Ratio: GE/GM

- Combine these elements . . .
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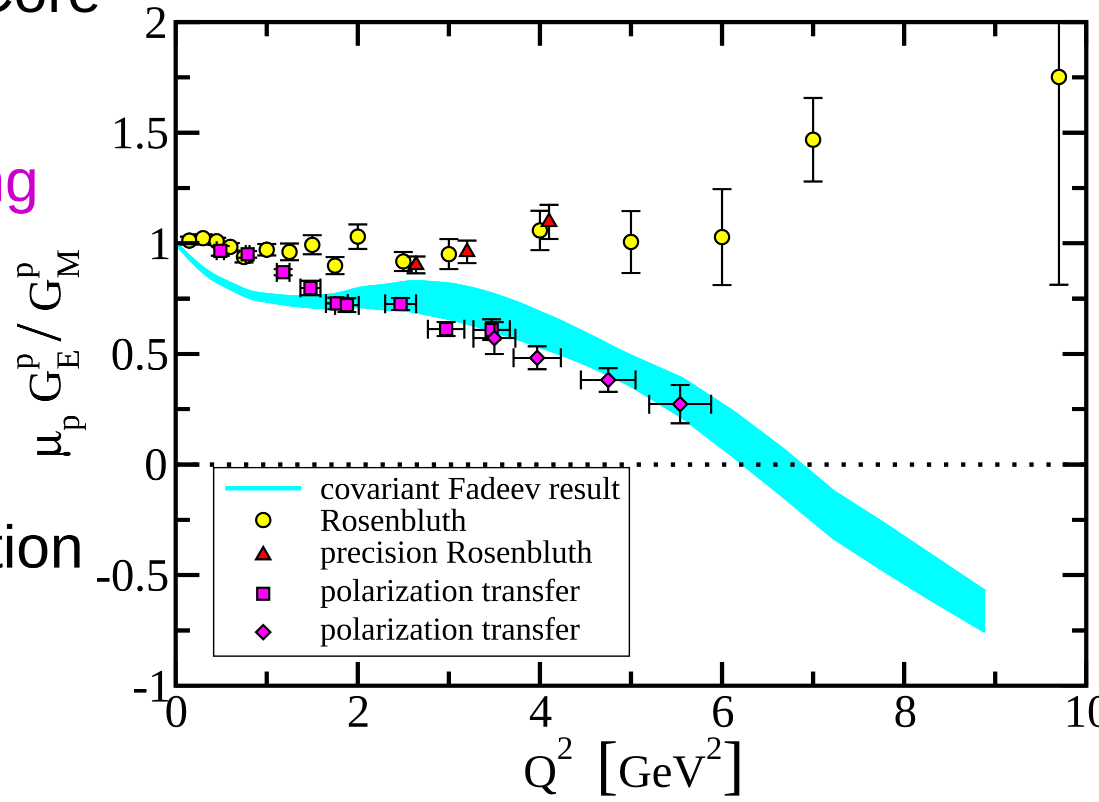

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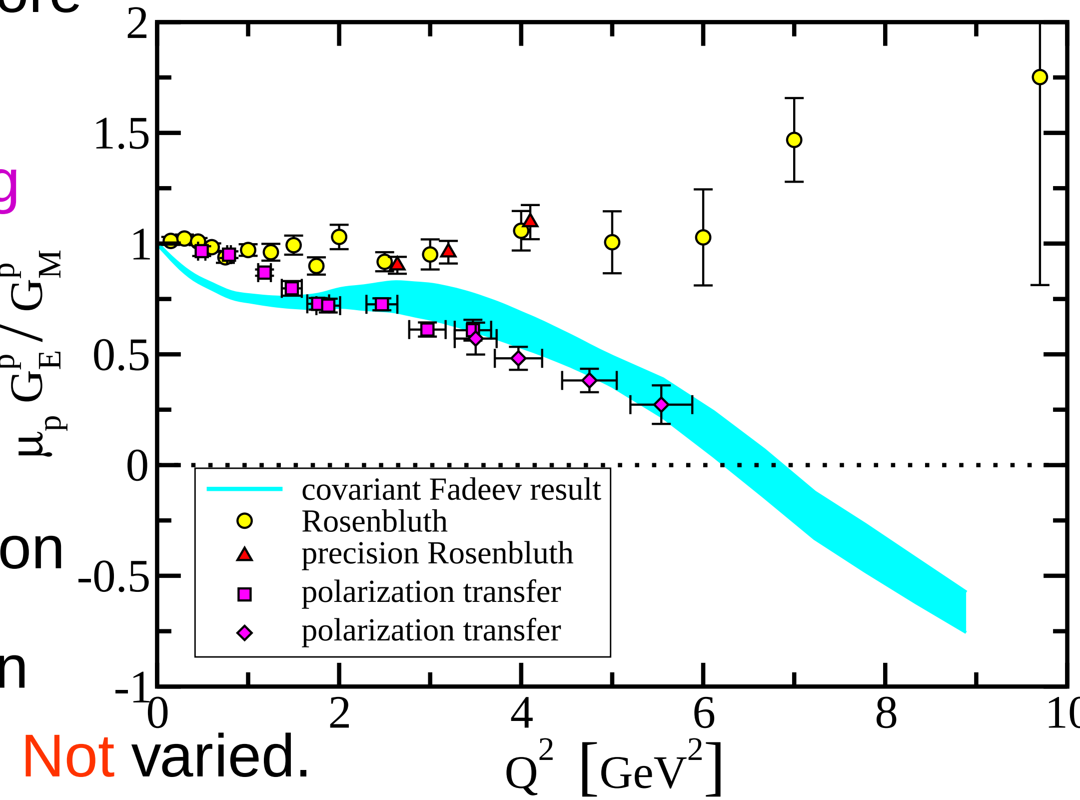

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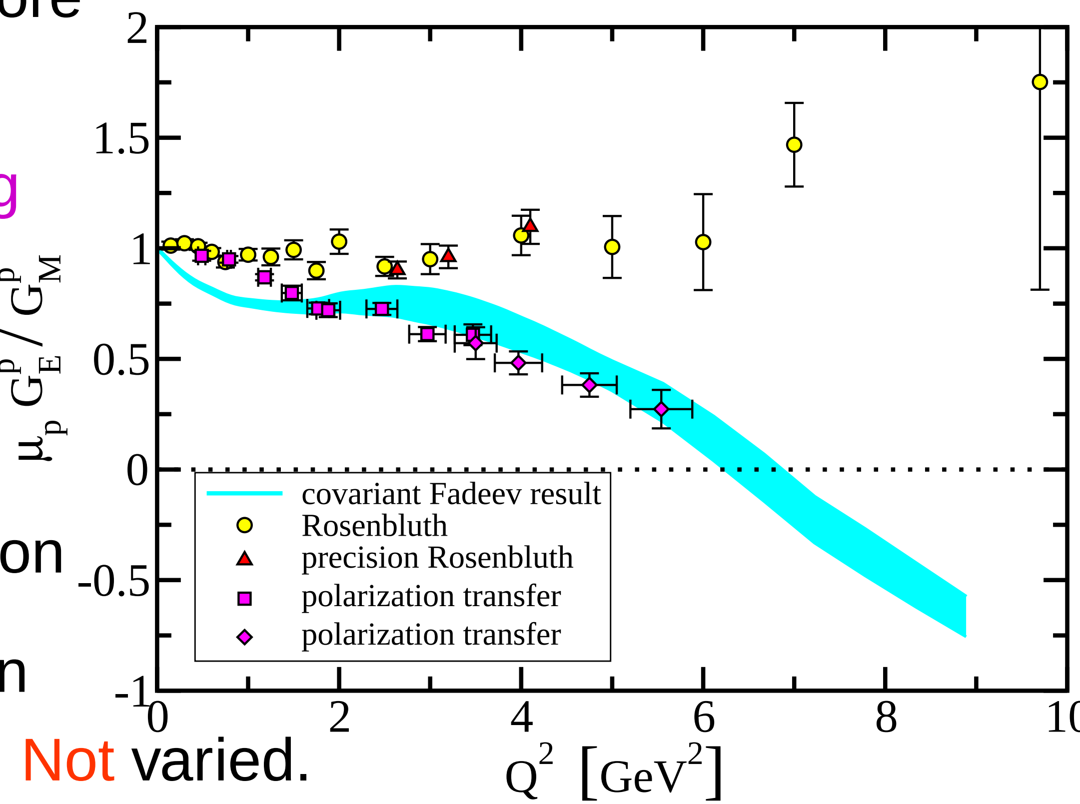

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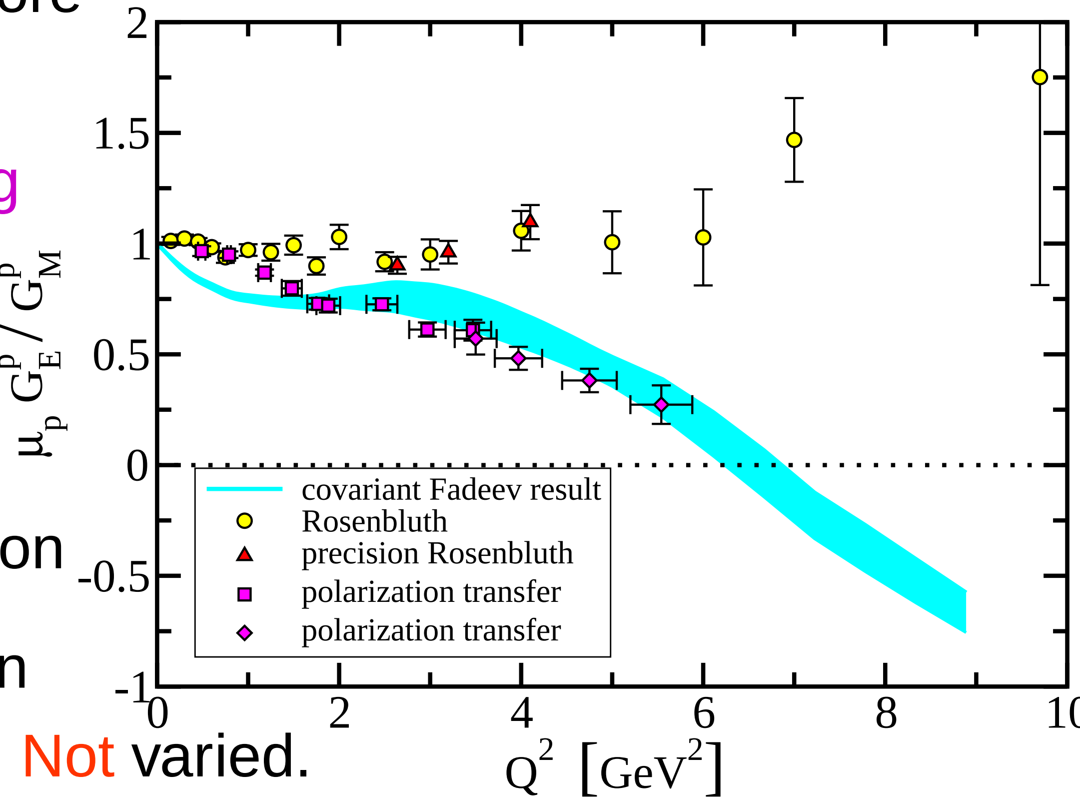

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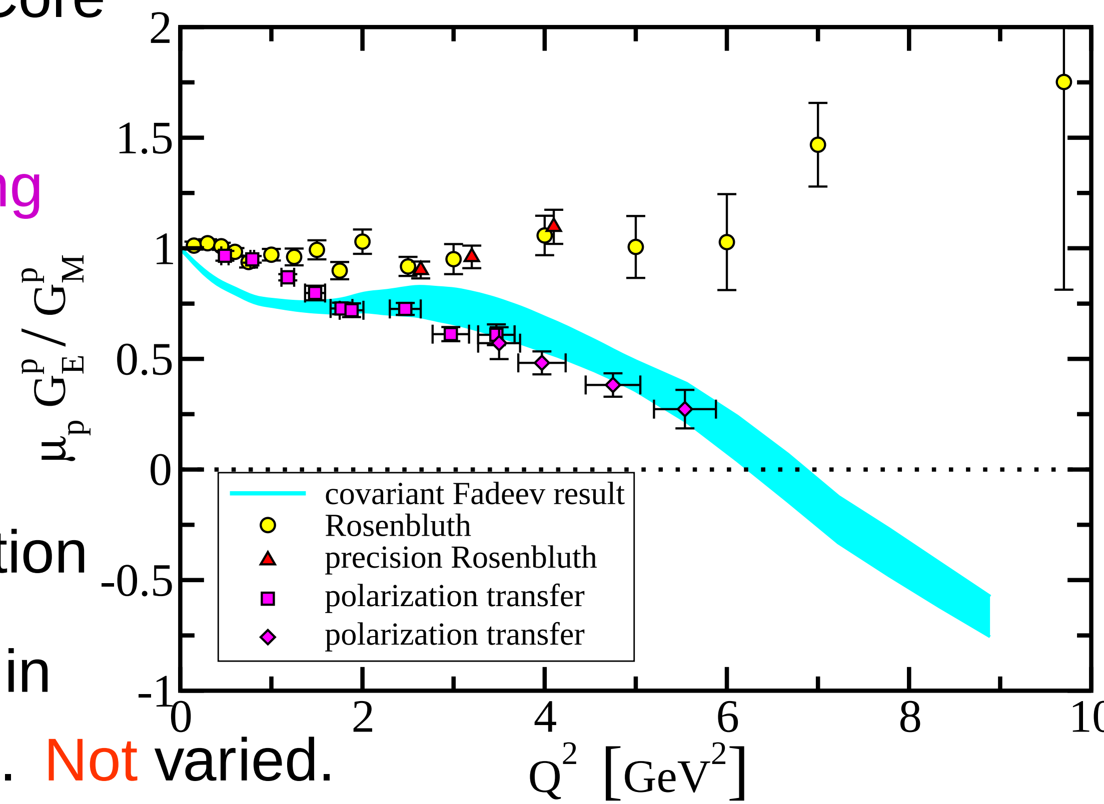

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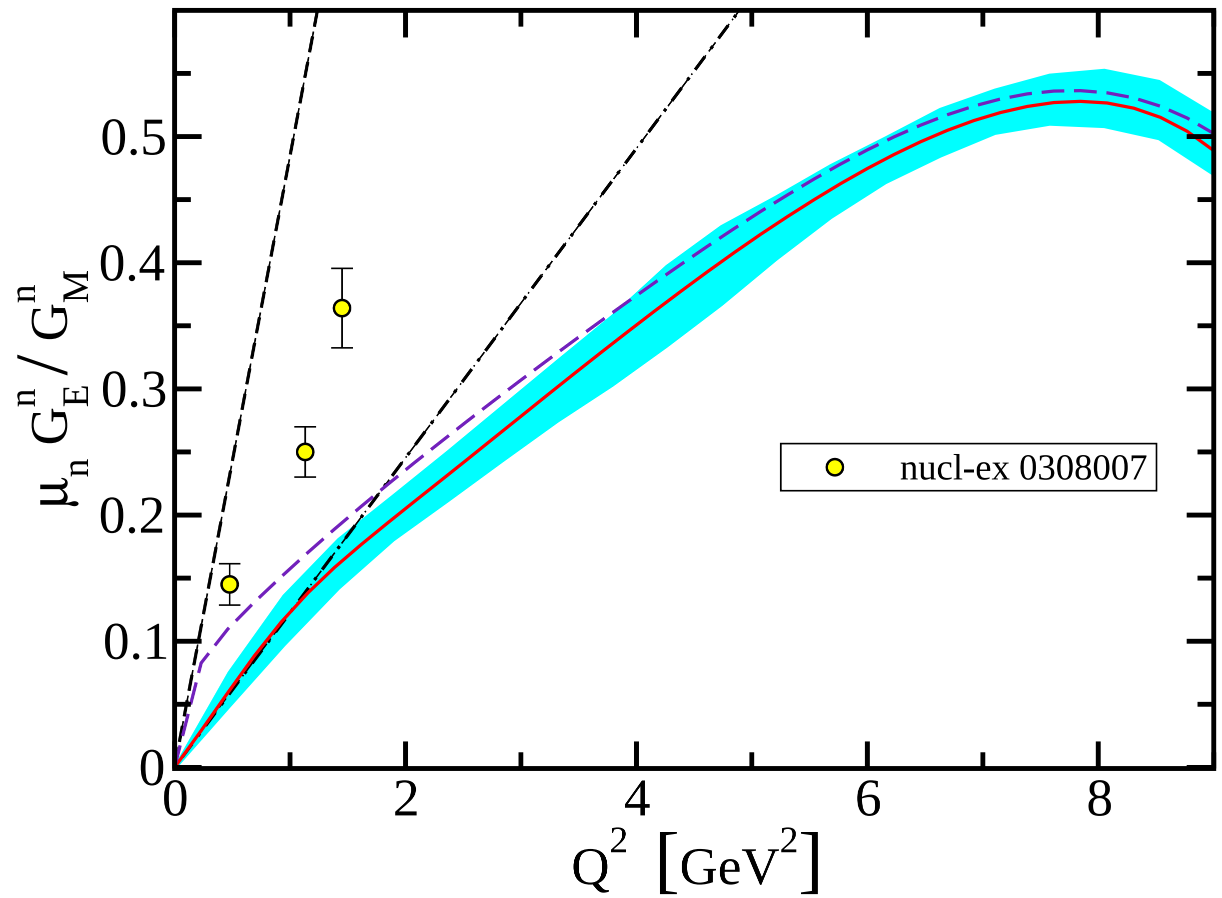
  - Predict Zero at $Q^2 \approx 6.5$GeV^2

Neutron Form Factors



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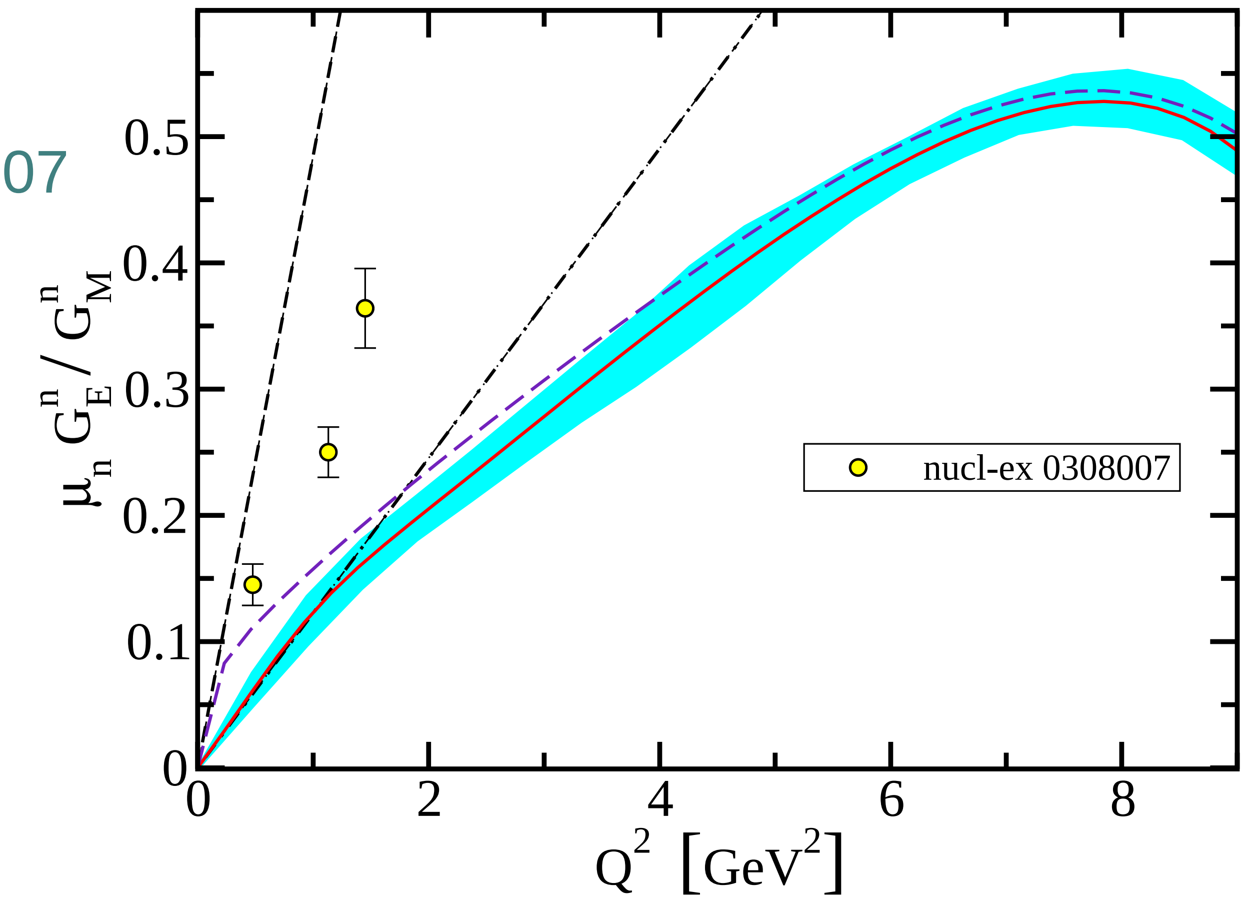
Neutron Form Factors

- Expt. Madey, *et al.* nu-ex/0308007



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Neutron Form Factors

- Expt. Madey, *et al.* nu-ex/0308007
- Calc. Bhagwat, *et al.* nu-th/0610080
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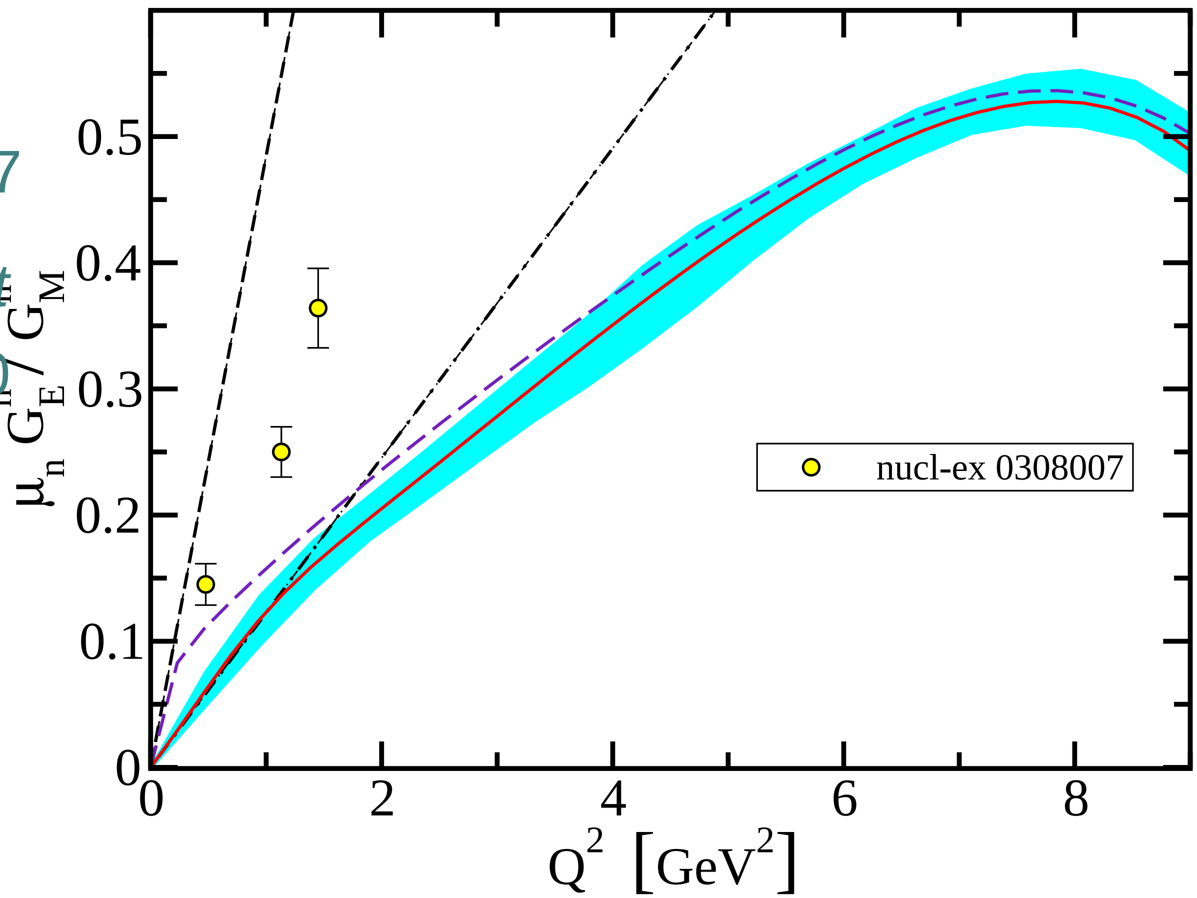
Valid for $r_n^2 Q^2 \lesssim 1$



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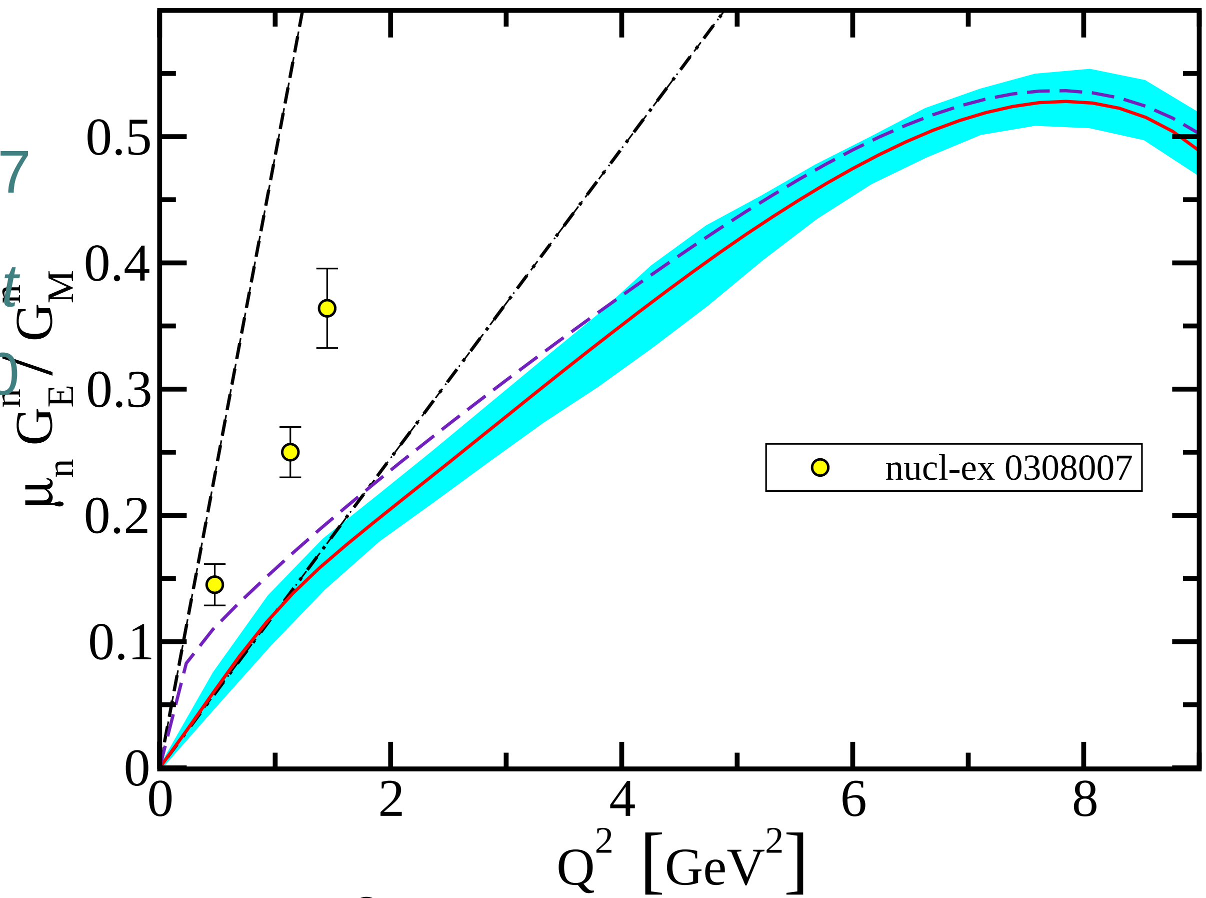

- No sign yet of a zero in $G_E^n(Q^2)$, even though calculation predicts $G_E^p(Q^2 \approx 6.5\,\mathrm{GeV}^2) = 0$
- Data to $Q^2 = 3.4$ GeV^2 is being analysed (JLab E02-013)

Epilogue

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- DSEs . . . contemporary tool that describes and explains these phenomena, and connects them with prediction of observables

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Contemporary Reviews

- Dyson-Schwinger Equations: Density, Temperature and Continuum Strong QCD
  C.D. Roberts and S.M. Schmidt, nu-th/0005064,
  Prog. Part. Nucl. Phys. **45** (2000) S1
- The IR behavior of QCD Green's functions: Confinement, DCSB, and hadrons . . .
  R. Alkofer and L. von Smekal, he-ph/0007355,
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- Dyson-Schwinger equations: A Tool for Hadron Physics
  P. Maris and C.D. Roberts, nu-th/0301049,
  Int. J. Mod. Phys. **E 12** (2003) pp. 297-365
- Infrared properties of QCD from Dyson-Schwinger equations.
  C. S. Fischer, he-ph/0605173,
  J. Phys. **G 32** (2006) pp. R253-R291
- Nucleon electromagnetic form factors
  J. Arrington, C.D. Roberts and J.M. Zanotti, nucl-th/0611050,
  J. Phys. **G 34** (2007) pp. S23-S52.

Colour-singlet Bethe-Salpeter equation

Detmold *et al*., nu-th/0202082

Bhagwat, *et al*., nu-th/0403012

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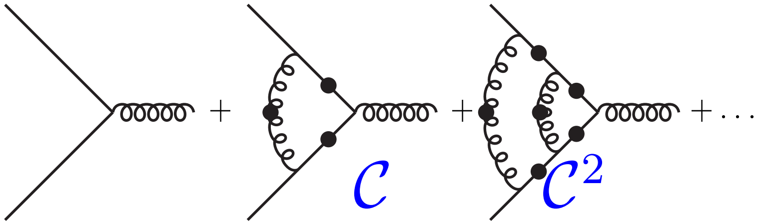
- Coupling-modified dressed-ladder vertex

$$\Gamma^a_\mu(k,p) \;=$$



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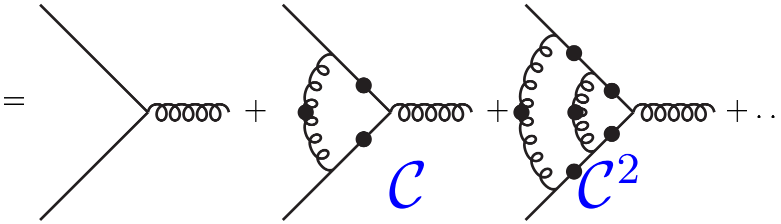

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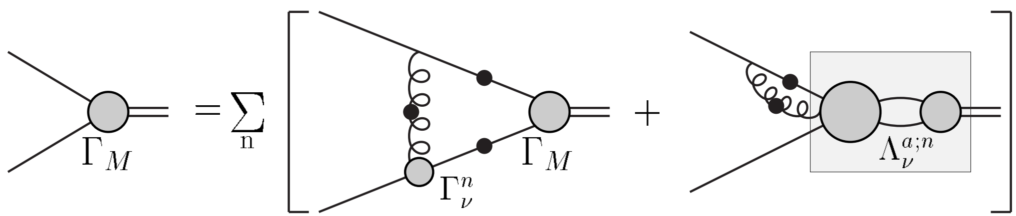

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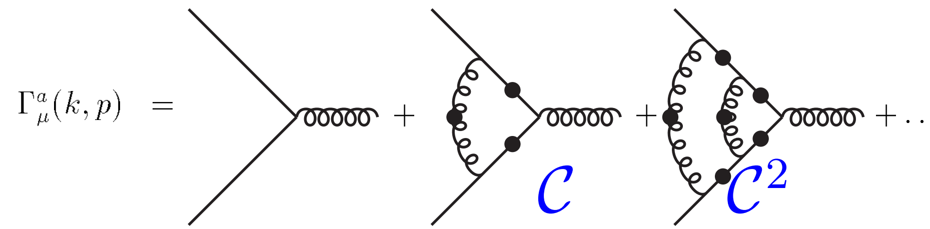

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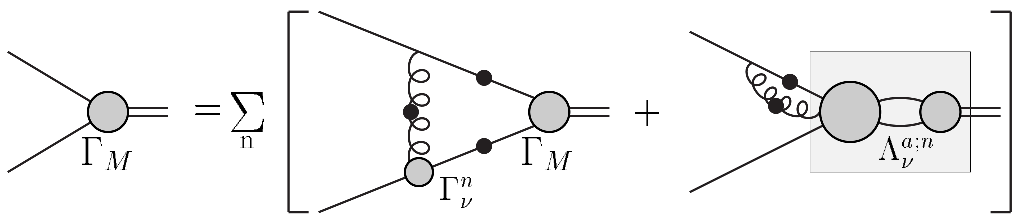
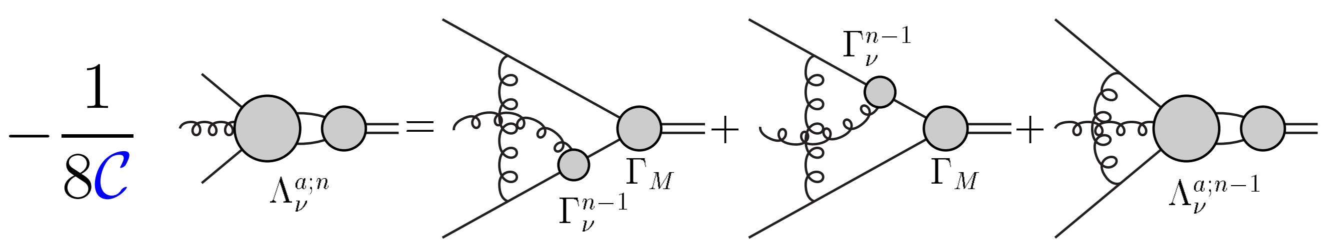


- Bethe-Salpeter kernel ... recursion relation



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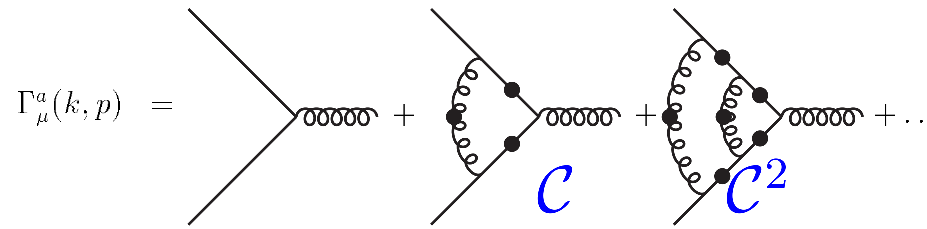

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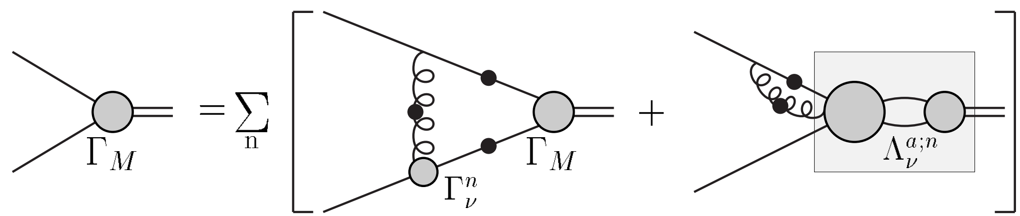

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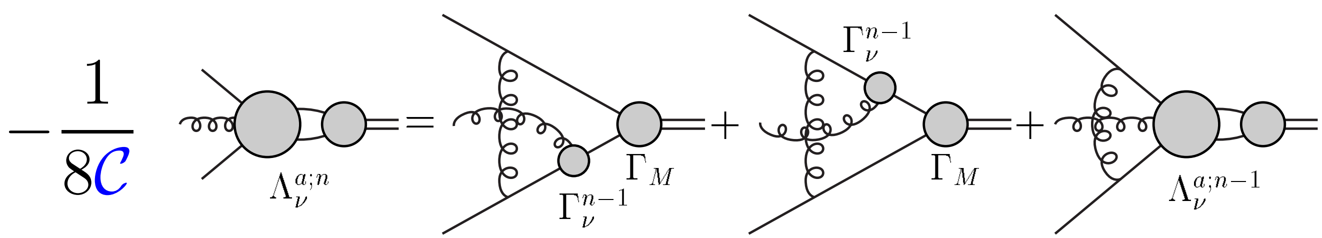

- Kernel necessarily non-planar,

  even with planar vertex

π and ρ mesons

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	$M_H^{n=0}$	$M_H^{n=1}$	$M_H^{n=2}$	$M_H^{n=\infty}$
π, $m=0$	0	0	0	0
π, $m=0.011$	0.147	0.135	0.139	0.138
ρ, $m=0$	0.920	0.648	0.782	0.754
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Deep-inelastic scattering

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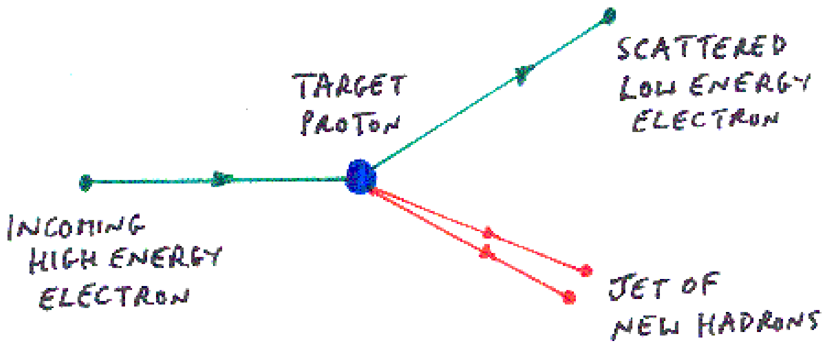
- Looking for Quarks

Deep-inelastic scattering



- Looking for Quarks

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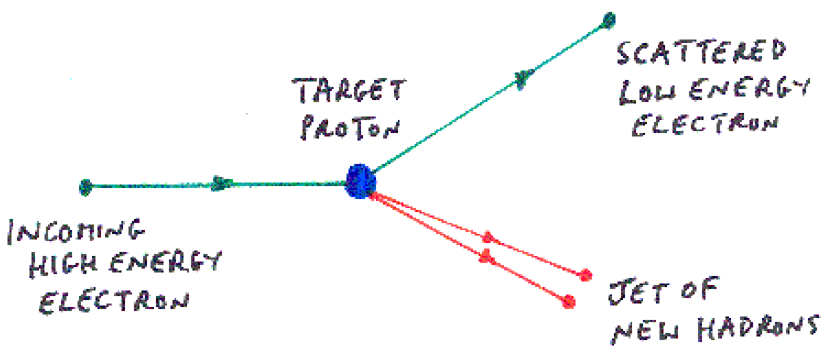
Deep-inelastic scattering



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- Signature Experiment for QCD:

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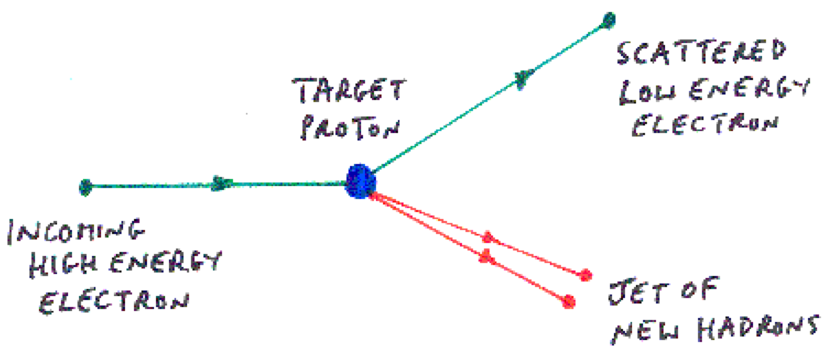

- Looking for Quarks

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- Cross-section: Interpreted as Measurement of Momentum-Fraction Prob. Distribution: $q(x)$, $g(x)$

Pion’s valence quark distn

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- π is Two-Body System: "Easiest" Bound State in QCD
- However, NO π Targets!

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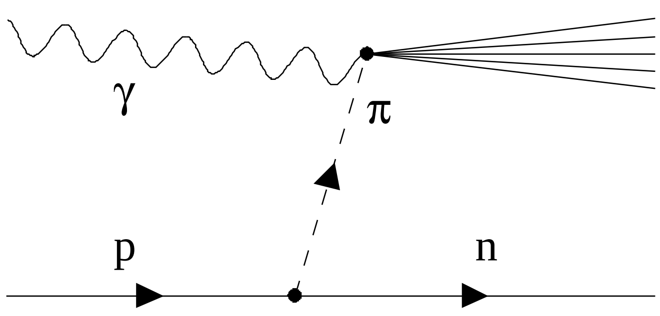
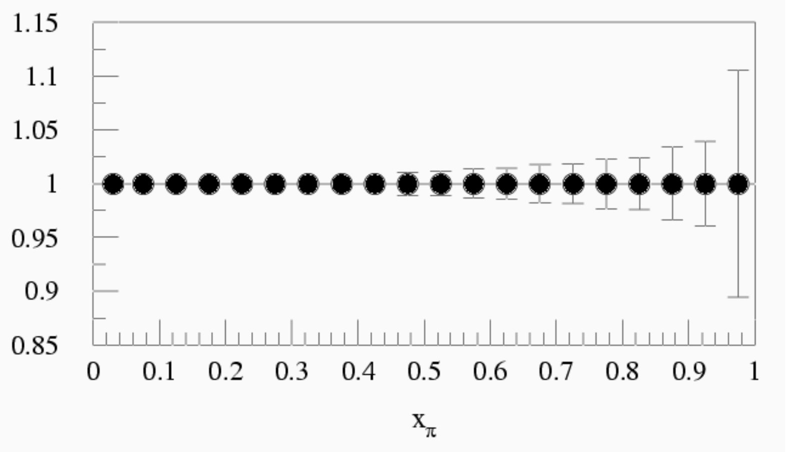
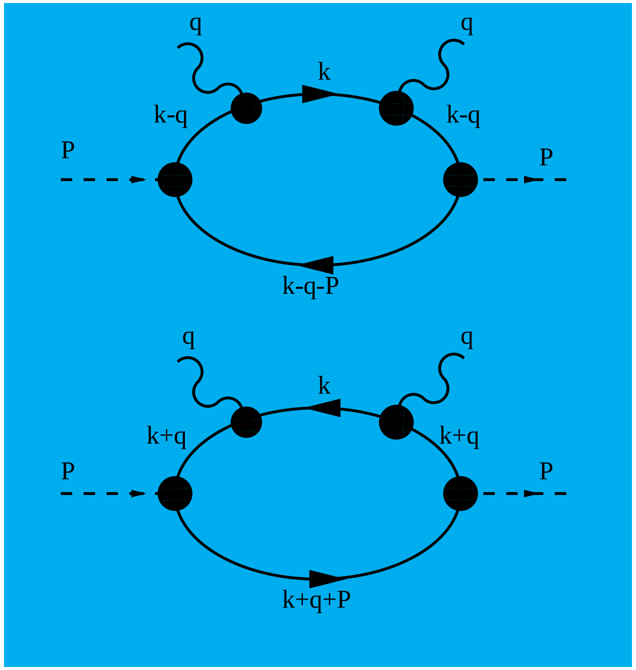
- Proposal (Holt & Reimer, ANL, nu-ex/0010004)

$e^-_{5\,\mathrm{GeV}} - p_{25\,\mathrm{GeV}}$ Collider $\to$ Accurate "Measurement"





Handbag diagrams



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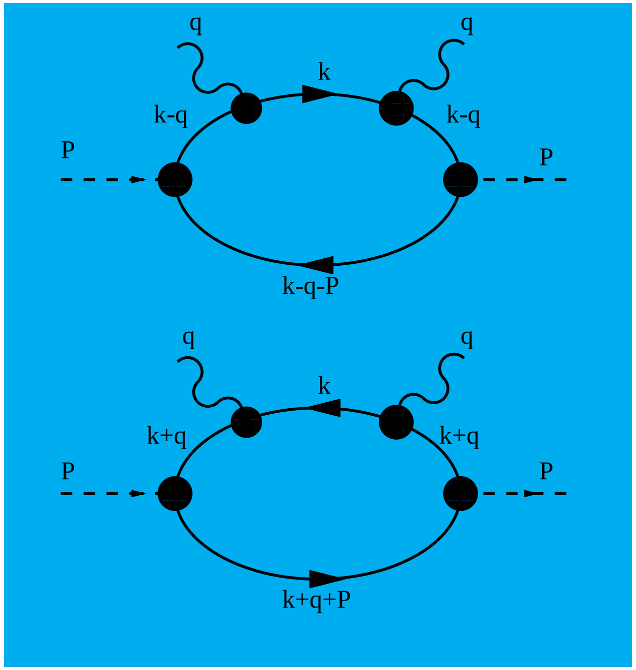


$$W_{\mu\nu}(q;P) = \frac{1}{2\pi}\mathrm{Im}\left[T^{+}_{\mu\nu}(q;P) + T^{-}_{\mu\nu}(q;P)\right]$$

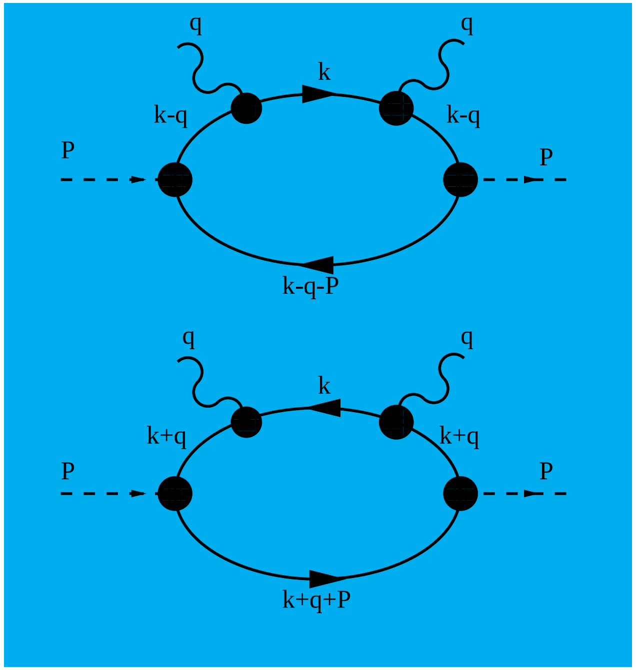
$$T^{+}_{\mu\nu}(q,P) = \mathrm{tr}\int\frac{d^4k}{(2\pi)^4}\,\tau_{-}\bar{\Gamma}_\pi(k_{-\frac{1}{2}};-P)\,S(k_{-0})\,ieQ\Gamma_\nu(k_{-0},k)$$
$$\times\, S(k)\,ieQ\Gamma_\mu(k,k_{-0})\,S(k_{-0})\tau_{+}\Gamma_\pi(k_{-\frac{1}{2}};P)\,S(k_{--})$$

Handbag diagrams

Bjorken Limit: $q^2 \to \infty\,,\;\; P\cdot q \to -\infty$

but $x := -\dfrac{q^2}{2P\cdot q}$ fixed.

Numerous algebraic simplifications



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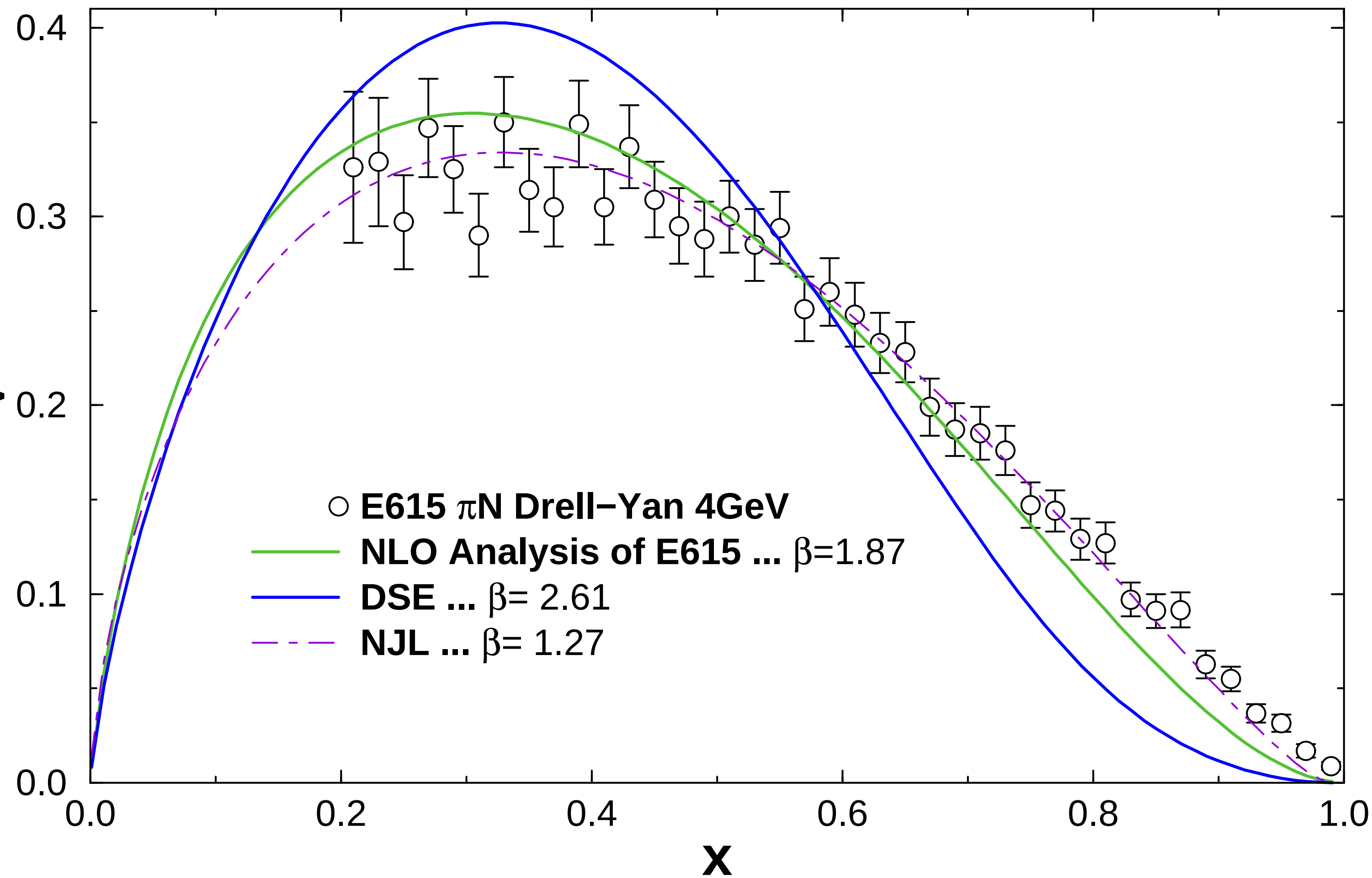
Extant theory vs. experiment

K. Wijersooriya, P. Reimer and R. Holt,
nu-ex/0509012 ... Phys. Rev. C (Rapid)



Nucleon's Quark Distribution Functions

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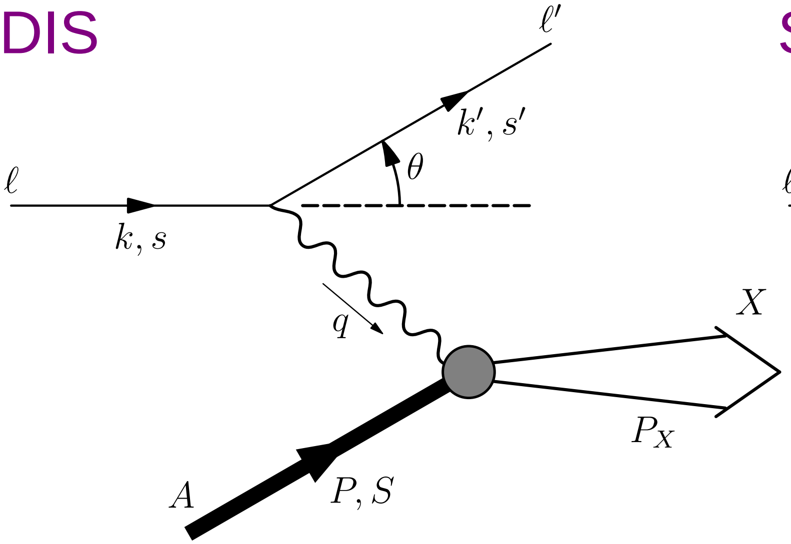
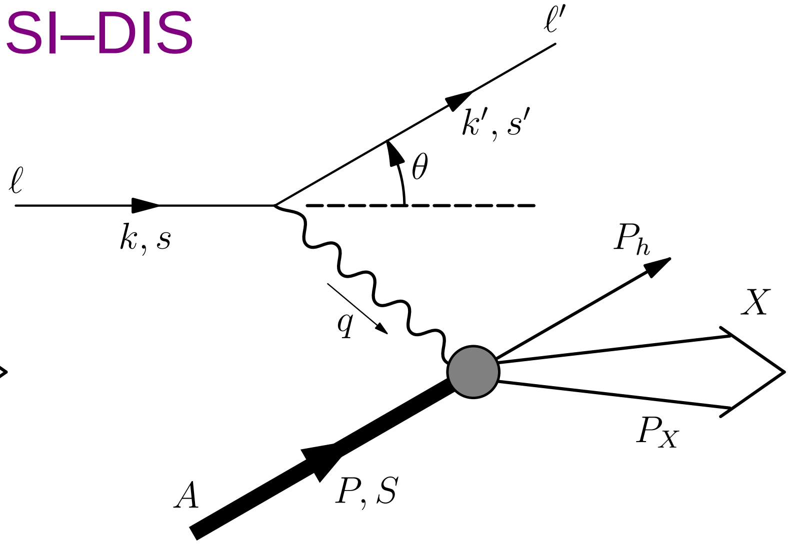
DIS



SI–DIS



Nucleon's Quark Distribution Functions

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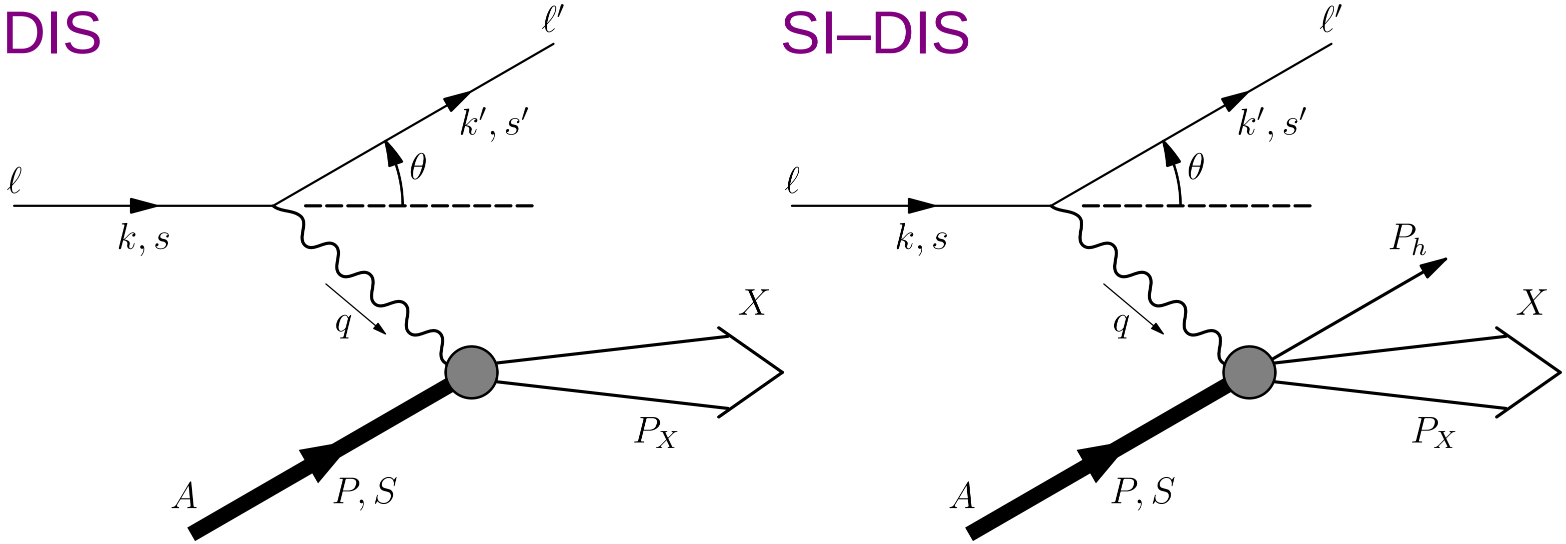

- Three twist-2 parton distributions $(k_\perp = 0)$:
  - Spin-Independent: $q(x)$
  - Helicity: $\Delta q(x)$
  - Transversity: $\Delta_T q(x)$
- All distributions have probability interpretation.
- By definition, contain essentially non-perturbative information about a given process.

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Definition and Sum Rules

Definition and Sum Rules

- Light-cone Fourier transforms :

$$\Delta_T q(x) = p^+ \int \frac{d\xi^-}{2\pi} e^{i\,x\,p^+\xi^-} \langle p,s|\overline{\psi}_q(0)\gamma^+\gamma^1\gamma_5\psi_q(\xi^-)|p,s\rangle_c$$

$$q(x) = \langle \gamma^+ \rangle, \qquad \Delta q(x) = \langle \gamma^+\gamma_5 \rangle$$

- Related to the nucleon axial & tensor charges via

$$g_A = \int dx[\Delta u(x) - \Delta d(x)], \quad g_T = \int dx[\Delta_T u(x) - \Delta_T d(x)],$$

- Must satisfy: positivity constraints and Soffer bound

$$\Delta q(x), \Delta_T q(x) \leqslant q(x), \quad q(x) + \Delta q(x) \geqslant 2\,|\Delta_T q(x)|$$

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Once more on the one that got away.

Cloët, Bentz, Thomas

arXiv:0708.3246 [hep-ph]

Model predictions

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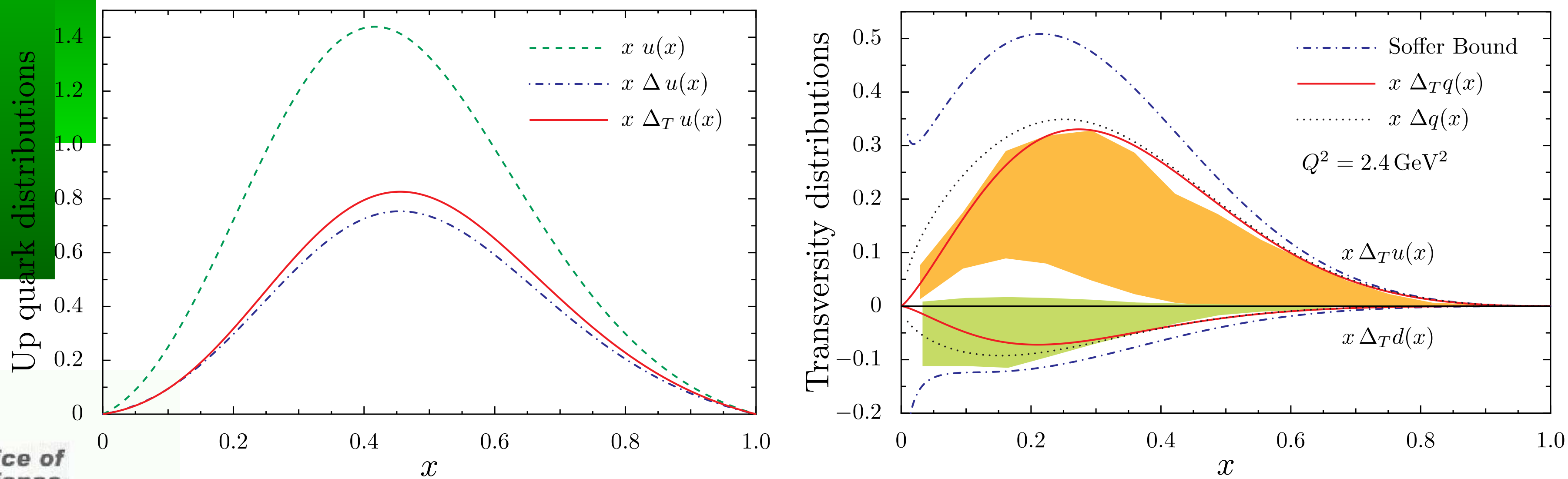
Model predictions

- Simplified Faddeev equation



- Satisfy: Soffer bound, baryon & momentum SRs.

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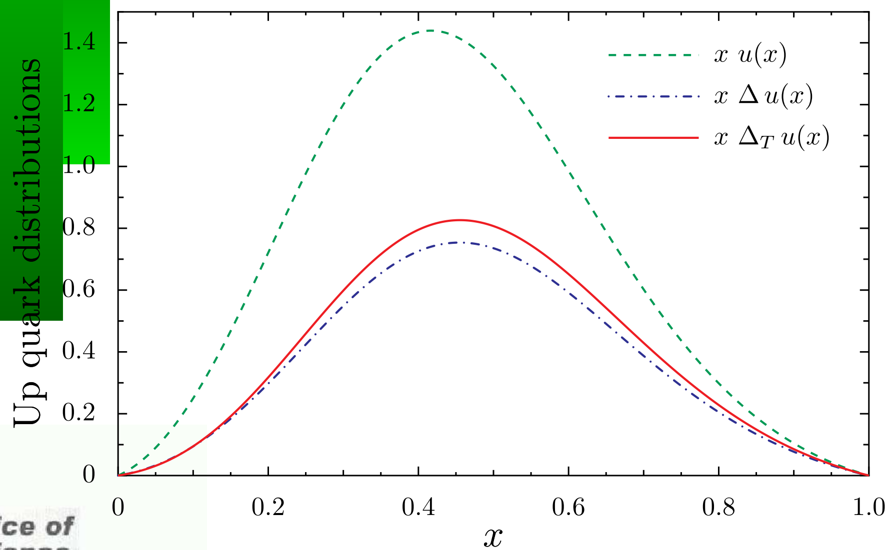

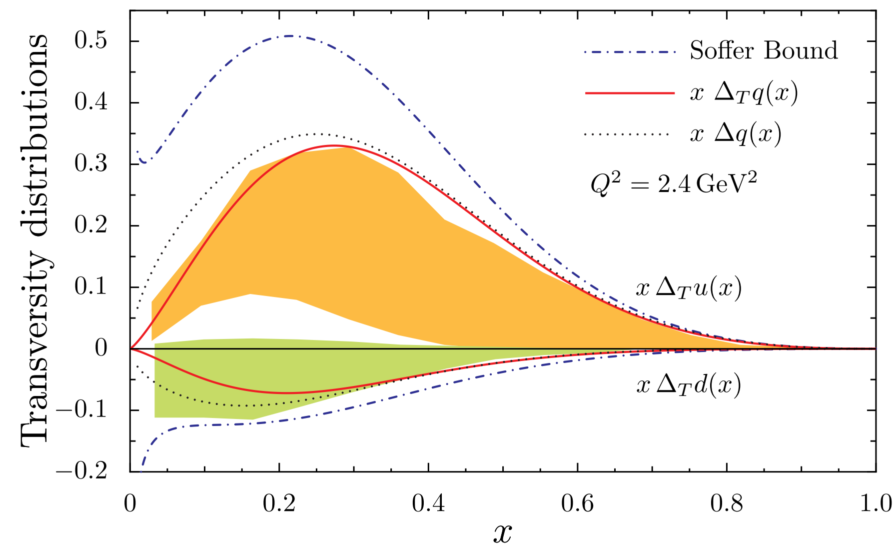

- Satisfy: Soffer bound, baryon & momentum SRs.
- Moments at $Q^2 = 0.16$ GeV^2:

$$\Delta u = 0.97, \quad \Delta d = -0.30 \implies g_A = 1.267$$

$$\Delta_T u = 1.04, \; \Delta_T d = -0.24 \implies g_T = 1.28$$

Model constraint

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Model predictions

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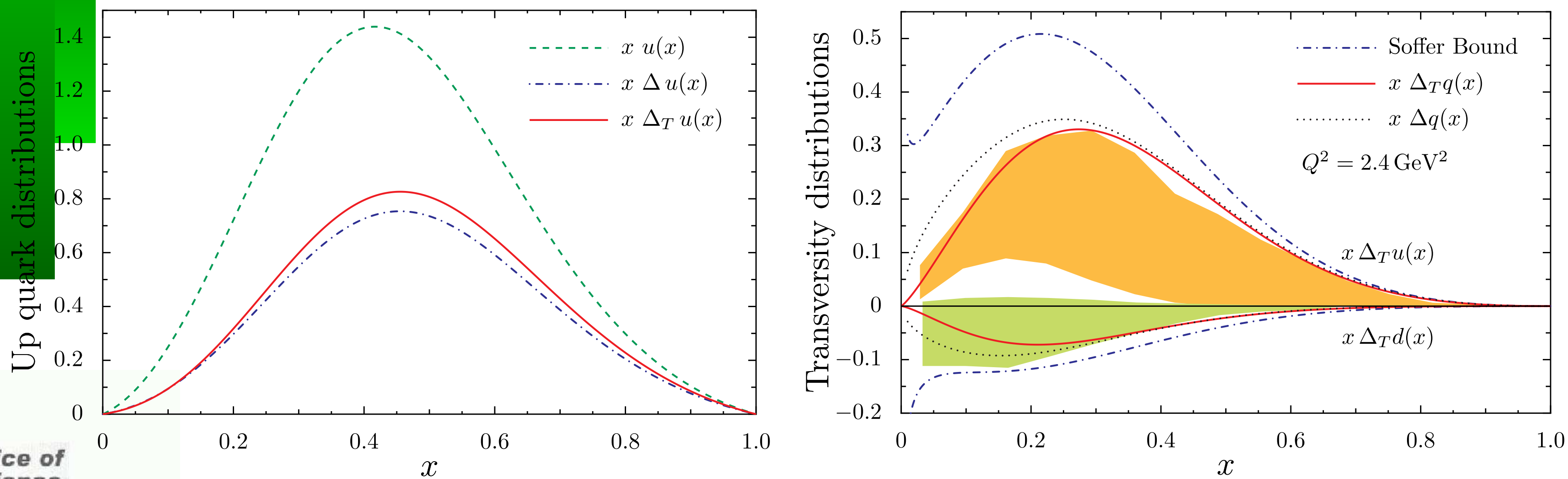

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- $\Delta q(x) \sim \Delta_T q(x)$ in valence region for $Q^2 \lesssim 10\,\text{GeV}^2$